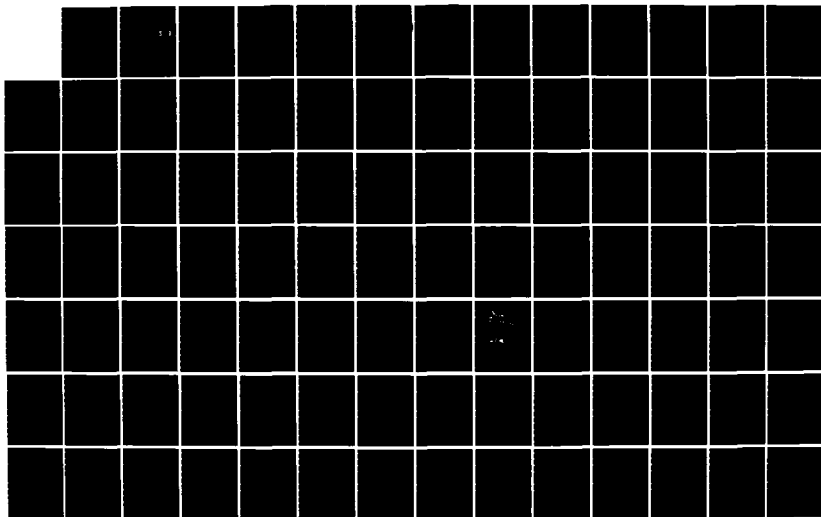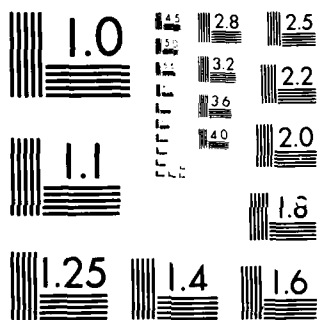AD-A163 828   COMPARISON OF ABSORPTION AND RADIATION BOUNDARY   1/2
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COMPARISON OF ABSORPTION AND RADIATION
BOUNDARY CONDITIONS USING A TIME-DOMAIN
THREE-DIMENSIONAL FINITE DIFFERENCE
ELECTROMAGNETIC COMPUTER CODE

THESIS

Clifford F. Williford
Captain, USAF

AFIT/GE/ENG/85D-53

DEPARTMENT OF THE AIR FORCE

AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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ELECTROMAGNETIC COMPUTER CODE

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Electrical Engineering

Clifford F. Williford. B.S.E.E

Captain, USAF

December 1985

Approved for public release; distribution unlimited

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Clifford F. Williford

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List of Symbols

A ...... generic quantity, 'A' = a vector, otherwise a
         magnitude in the subscripted direction (could
         be E-field or H-field).

ABC .... Absorption Boundary Condition.

c ...... speed of light (3 X 10^8 meters/second).

det .... determinant of the matrix which follows.

E-field (E) electric field (volts/meter), underbar
         indicates a vector quantity, subscript indicates
         magnitude in subscripted direction.

f(a) ... 'f' is a function of 'a'.

f{i,j,k} 'f' value evaluated at the point i,j,k.

x,y,z .. magnitude in a particular direction as defined by
         the Cartesian coordinate system.

$\hat{x},\hat{y},\hat{z}$ .. unit vector in direction as defined by Cartesian
         coordinate system.

h ...... small distance (or increment) as used in the
         definition of a derivative.

H-field (H) magnetic field (ampere/meter), underbar
         indicates a vector quantity, subscript indicates
         magnitude in subscripted direction.

I ...... current (ampere).

i,j,k .. number designating a location in a three-
         dimensional grid space in a Cartesian coordinate
         system relative to x,y,z.

J ...... current density (ampere/meter^2).

N ...... integer number of number of cells in problem space.

r ...... radius (meter).

RBC .... Radiation Boundary Condition.

t ...... time (seconds).

< ...... left side less than right side.

3DFD ... three-dimensional finite-difference computer code
by Rymes'.

$\nabla \times$ .... curl operator.

$\nabla \cdot$ ...... divergence operator.

ϵ ...... (epsilon) permittivity (farad/meter).

μ ...... (mu) permeability (henry/meter).

ρ ...... (rho) electric charge density (coulomb/meter^3).

σ ...... (sigma) conductivity (mho/meter)

Δ ...... (delta) small increment as in a derivative.

(#) .... general reference to entire reference # found in
the bibliography.

(#:##) . reference from page ## of bibliography reference #.

(#;##) . general reference from reference # and ##.

(#:##;a) reference #, page ## and general reference 'a'.

{ } ... standing alone defines a point in the problem space
(e.g., {i,j,k}).

∂ ...... partial derivative

π ...... (pi) = 3.14

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Abstract

The Three-Dimensional Finite Difference (3DFD) computer code
is compared using Absorption Boundary Conditions (ABS)
versus Radiation Boundary Conditions (RBC). This comparison
is made when the 3DFD code is used to study the interaction
of lightning with an aircraft. The 3DFD computer code is a
modified version of Rymes' 3DFD. The aircraft modeled for
the paper is an F-16 'Fighting Falcon'. The ABC used
simulates an infinite free-space by setting the conductivity
of the boundary space to that of distilled water, to
"absorb" the outgoing electromagnetic waves. The RBC
simulates free-space by assigning the boundary fields to a
previously calculated value. The value is calculated with a
parabolic interpolation of three previous field values,
which are offset in space. Therefore, the calculated value
is also extrapolated to account for the time delay and
position change. The results of incorporating RBC were
dramatic. The ten locations sampled for the test showed
marked improvement in the waveforms when using RBC's.
Depending on the purpose of the analysis, this improved
waveform output may be overshadowed by the 25% increase in
CPU time that is needed for the more sophisticated RBC.

1. <u>Introduction</u>

This thesis compares Radiation Boundary Conditions (RBC) with Absorption Boundary Conditions (ABC) in a time-domain three-dimensional finite difference computer code (3DFD). In this application, the 3DFD computer code is used to analyze lightning's electromagnetic interaction with an F-16 aircraft. The major tasks accomplished during this thesis effort include:

    a. The F-16 'Fighting Falcon' aircraft was electromagnetically modeled, and implemented in a modified version of the Rymes' 3DFD code (16).

    b. The 3DFD code with its original absorption boundary conditions was updated, corrected and run for a typical nose-to-tail lightning strike (Appendix 1) (48). The fields calculated were recorded at 10 monitor locations on the F-16 aircraft (Appendix 3).

    c. The 3DFD code was then modified to implement the radiation boundary conditions (Appendix 2) (59).

    d. The 3DFD code with the new radiation boundary conditions was run for the same nose-to-tail lightning strike on the F-16

geometric model. The fields calculated were sampled and recorded at the same 10 locations during both runs (Appendix 3).

e. The results of the two computer runs for the first two microseconds were compared (Chapter 6). The comparisons were based on one complete run with the absorption boundary conditions and one run with the radiation boundary conditions. The comparisons were made for the same 10 sample points on the F-16 (Appendix 3).

The F-16 was geometrically modeled and implemented into computer code in a manner suitable for analysis by a modified version of the Rymes' 3DFD computer code (48; 16). The Rymes' 3DFD code was modified and used by 1Lt Hebert at the Air Force Wright Aeronautical Laboratories Atmospheric Electricity Hazards Group (AFWAL/FIESL), Wright-Patterson AFB, Ohio (16). Hebert implemented the code with absorption boundary conditions, and modeled a CV-580 aircraft for his study (16). During this thesis effort radiation boundary conditions similar to those discussed in a paper by Kunz and Lee were developed, encoded, and written into the modified 3DFD code (27). The computer codes were run for a direct lightning strike, nose-to-tail, on an F-16 aircraft. The results are compared and presented in this thesis.

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Lightning

Lightning brings to mind a flash of light in the sky, a loud clapping sound and rumbling thunder. This flash of light and the associated sounds are the discharging and neutralization of the atmosphere's large charge centers from one cloud to another, or from clouds to the earth (61:1). Lightning in this text is to be thought of as a high current electric discharge which has a path length measured in kilometers (61:1). Aircraft in the presence of these highly charged areas can become part of the high current channel (35:90-1). In fact, Mazur believes the aircraft itself triggers lightning (35:90-2). Shaeffer agrees with this, except with the qualification that a highly charged air mass, one which is conducive to a lightning discharge, must already exist before the aircraft can trigger the lightning discharge (50:67).

Lightning and Aircraft

Lightning poses a possible catastrophic threat to any aircraft (11:i). Lightning strikes account for more than one-half of the total USAF weather-related aircraft mishaps (36:vi). Since little can be done to prevent an aircraft from being struck by lightning, aircraft protection for the critical components is of utmost importance (45). Critical

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components, such as flight control computers, fuel systems, and structurally critical airframe/propulsion units, are vulnerable to electrical disruption and/or mechanical failure (45). As electronic complexity has increased, the size and weight have decreased. However, the probability of lightning strikes has remained relatively constant (40:8). It is interesting to note that Pierce concludes, using basically the same logic, that the lightning hazard to aircraft operation is increasing (42:17). Therefore, the importance of characterizing lightning and its effects is of growing importance, as indicated by the number of articles written on the subject (8; 23; 31; 35; 36; 40; 42; 43; 46; 47; 49; 50). An aircraft, such as the F-16, with a "fly-by-wire" flight control system, were it unprotected, could be rendered inoperable by a lightning strike (1:1).

The starting point in characterizing lightning's effects with a computer program is to model the aircraft's outer skin. Studying the propagation of the electromagnetic energy from the entry to the exit point, as it redistributes on the surface of the aircraft's fuselage, is the first goal (34:2,16). Determining this redistribution can lead to coupling the surface currents to the interior components. The final goal is understanding lightning's effect on the sensitive electronic components, and then protecting sensitive components from these effects. An accurate computer code could be a valuable tool in designing

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protection against lightning's effects. It would allow
protection to be designed and tested before the production
stage of new aircraft development.

All-metal aircraft are shielded from many of
lightning's effects, as the all-metal skin presents a
Faraday cage type enclosure for the electronics bay (19; 45;
52; 58). Recent efforts to use the new, lighter, advanced
composite and thermoplastic materials in aircraft reduces
this shielding protection (10:1). As early as 1952, Burkley
was looking at plywood, plastics, laminated fiberglass, and
other non-conductive materials to be used as aircraft
structural components (5). Burkley was studying the effects
of, and the necessary protection needed from, the high
current surges associated with lightning strikes on these
non-conductive materials (5). Examples and techniques of
various protection schemes can be found in numerous sources.
Sommer of Boeing Company, Weinstock of McDonnell Aircraft
Company, and Fisher of General Electric are just three of
the many authors publishing in this area of aircraft
lightning protection (51; 63; 14).

Electromagnetic Computer Codes

Electromagnetic computer codes allow the engineer to characterize and study the electromagnetic interaction with aircraft. The engineer can then design protection against those effects which cause electronic upset or damage. As previously stated, the use of advanced composite materials and sensitive microelectronics in more modern aircraft makes them more susceptible to the effects of lightning strikes. This increased susceptability demands more accurate electromagnetic modeling (46:220). This modeling is to be used in the development of lightning protection. Accurate models, when used in design for lightning protection, allow the use of optimal lightning protection. This protection is optimal in that excessive lightning protection would add weight that is not in proportion to the risk reduction gained (63:34-1).

While accurate, these models must also be flexible enough to handle new lightning channel models. A recent inflight lightning characterization program has shown that intracloud lightning attachment is even more severe than previously estimated, with faster risetimes and higher charge transfers (19:1). This demonstrates the need for flexible analysis systems which can be easily modified to incorporate new findings without completely reworking each study.

Many electromagnetic computer codes are available to
approximate a solution to Maxwell's equations (2; 13; 28;
34; 60). One type of code solves Maxwell's equations in the
integral form based upon Harrington's Method of Moments,
such as Auckland's study of an F-14 (15; 4). Another type
of code solves Maxwell's equations in their differential
form using the Finite Difference Method of approximation,
such as Holland's "THREDE" (20; 21; 22). The time-domain
finite difference electromagnetic code approximation of
Maxwell's equations was used during this thesis effort. In
a study by Longmire of Mission Research Corporation, it is
stated that the finite difference method is the fastest way
of solving Maxwell's equations (33:2341). And, in a recent
article, Mei states that he believes the finite difference
method is the most adaptable to the virtual memory systems
of minicomputers which are in growing use in industry
(37:1145).

Background

In the study of lightning's interaction with aircraft,
it is often necessary to have a computer model for
analytical comparisons. Hebert has successfully modified a
finite difference electromagnetic code written by M.D. Rymes
of Electromagnetic Applications, Inc., to analyze a CV-580
lightning strike aircraft test-bed (48; 16). Other

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modifications to Rymes 3DFD code and an expanded user's guide are detailed in Hebert's report (16). This modified 3DFD code presently uses absorption boundary conditions (Appendix 1), which cause the boundaries to artificially reflect unabsorbed electromagnetic energy. This gives less than desired accuracy, as the reflected waves return to the aircraft's surface at later time steps (55:626).

3DFD is a finite difference formulation of the time-domain electromagnetic-field problem. This code's major advantage is that it does not require the memory or the time needed to invert the matrices encountered in the MOM codes (33:2340). As Mur states it, though, the finite difference method has as its major problem the limited size of the problem space (41:377). It must be remembered that it is the problem space size that is the problem, not the size of the object inside. For example, an aircraft as large as a B-52 has been studied using 3DFD (21). A Cartesian finite difference method uses a rectangular problem space, totally enclosing the object to be studied (e.g., aircraft). The object to be studied is defined in the problem space by assigning values of permittivity and conductivity to each component of the total electric field (E-field), which describes the geometry of the object. This geometry has the restriction of being described by a limited number of predetermined rectangular shapes, which make up the problem space in the Cartesian coordinate system.

The computer code solves Maxwell's time dependent curl equations, which in turn solve the boundary conditions for the object in a "natural way" (62:397). The code progresses through the problem space in time steps using an algorithm originally developed by Yee (64). Since an infinite problem space cannot be defined on the computer, difficulties arise when the propagating wave reaches the problem space boundary. These boundaries cause reflections unless they are modified to account for the ideal analytical situation of free space. Thus, additional algorithms are needed to account for the radiation conditions. Taylor was the first to implement Yee's algorithm. He used absorption boundary conditions to account for the previously-mentioned reflections at the problem space boundaries (59:585).

Yee originally started with "hard" lattice truncation (another way of expressing the boundary condition) (64). Hard lattice truncation is defined as forcing the outside boundary of the problem space to be a perfect conductor. This is done by assigning the tangential E-field the value of zero at the boundary (55:626). This is also known as "tin can" boundary conditions, as the problem space is totally enclosed by perfectly conducting metal boundaries (16:22).

The two methods that are examined in this thesis are both referred to as either "soft" lattice truncation methods, or "soft" boundary conditions. These are the

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absorption boundary condition and the radiation boundary condition. The absorption boundary condition is accomplished by assigning increasing values of conductivity to the cells of the problem space near the boundaries, thereby effectively chipping away at the E-field, a small amount at a time (55:626). The other method, the radiation boundary condition, reduces the magnitude of the E-field by a factor of $1/r$, which is the radiation condition characteristic of an electromagnetic wave propagating in free-space (39:41). Here 'r' is the radial distance from the origin of a centrally located coordinate system.

The finite difference codes have been found to agree, within 1 dB and 1 lattice cell, with known analytical and experimental quantities (54:202). Due to the accuracy and efficiency of Yee's basic algorithm, Taflove, Kunz, Umashankar, Merewether, Fisher, Mei, and others have published many papers on combined methods, hybrids, curved surfaces, and other modifications, making this a very competitive method for a numerical solution of Maxwell's equations (14; 26; 37; 38; 56; 62).

Problem

First, an electromagnetic model of an F-16 aircraft had to be implemented on the computer for a new study using the present modified code. During the computer runs using the absorption boundary conditions (ABC), sample data from several points was stored for further study. This required the correct geometrical modeling of the aircraft into the three-dimensional finite difference problem space. Next, the code was modified to incorporate the radiation boundary conditions (which were believed to limit previous reflections). Then the code was run with the same F-16 model, sampling the same points as before. The final task was to compare the results of both computer runs and analyze the findings.

Scope

This study was limited to developing a geometrically correct electromagnetic model of the F-16 using the subroutine AIRPLN from an AFWAL/FIESL technical report by 1Lt Hebert (16). The subroutine AIRPLN, modeling an F-16, was run with the present modified computer code for a nose-to-tail lightning strike. Samples were recorded at 10 locations (7 H-fields and 3 E-fields) for predetermined orientations. The code was then changed to incorporate the

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radiation boundary conditions (RBC). The modified version of the code with radiation boundary conditions was run with the same subroutine AIRPLN . The same 10 sample points were recorded and the results were analyzed.

Assumptions

The assumptions were that the AFWAL/FIESL technical report, and previous studies which determined that RBC would be more accurate than ABC, were correct (16). An isotropic, linear, and homogeneous medium was considered. The region of interest was considered source-free except for the injected lightning strike.

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2. Theory

The three-dimensional finite difference code uses the time-domain differential form of Maxwell's equations (64:302). The E-field and H-field magnitudes in each of the three vector directions that define the Cartesian coordinate system are calculated using these equations (64). The calculations are made while stepping through the grid problem space (NxNxN) at a particular time. It is necessary to increment the time step after each complete pass through the grid space calculating the E-field or H-field. All units are in the MKS system unless otherwise specified. The form of Maxwell's equations for isotropic material used here is (24:361)

$$\mu \frac{\partial \underline{H}}{\partial t} = - \nabla \times \underline{E} \qquad\qquad (2.1)$$

$$\varepsilon \frac{\partial \underline{E}}{\partial t} = \nabla \times \underline{H} - \sigma \underline{E} \qquad\qquad (2.2)$$

$$\nabla \cdot (\varepsilon \underline{E}) = \rho \qquad\qquad (2.3)$$

$$\nabla \cdot (\mu \underline{H}) = 0 \qquad\qquad (2.4)$$

where

```
        H = magnetic field (amps/meter)
        E = electric field (volts/meter)
        t = time (seconds)
        μ = (mu) permeability (henry/meter)
        ε = (epsilon) permittivity (farad/meter)
        ρ = (rho) electric charge density (coulomb/meter³)
        σ = (sigma) conductivity (mho/meter)
    ∇ x = curl operator
    ∇ . = divergence operator
```

These are point relationships ($J = \sigma E$). In the finite difference code, the term 'decentralizing mesh' is often used to refer to the gridding of the problem space. This is not to be confused with the mesh relationship of the integral form of Maxwell's equations.

A necessary process in understanding the finite difference code is to develop the three-dimensional finite difference form of Maxwell's equations. This development will be using a central differencing estimation for a derivative (32:163). The first operation in the process is to put Maxwell's equations in a finite difference form. Then one must both understand where the fields are located in the problem space, and comprehend the makeup of the problem space itself. In particular, the single point reference system references fields located on three sides of the rectangular box. A point in the three-dimensional grid, and the associated fields are shown in Figure 1. Finally, one must put all of this together and express the three-dimensional finite difference equations in a form useful to algorithm development. A source-free region is considered for the development of the algorithm.

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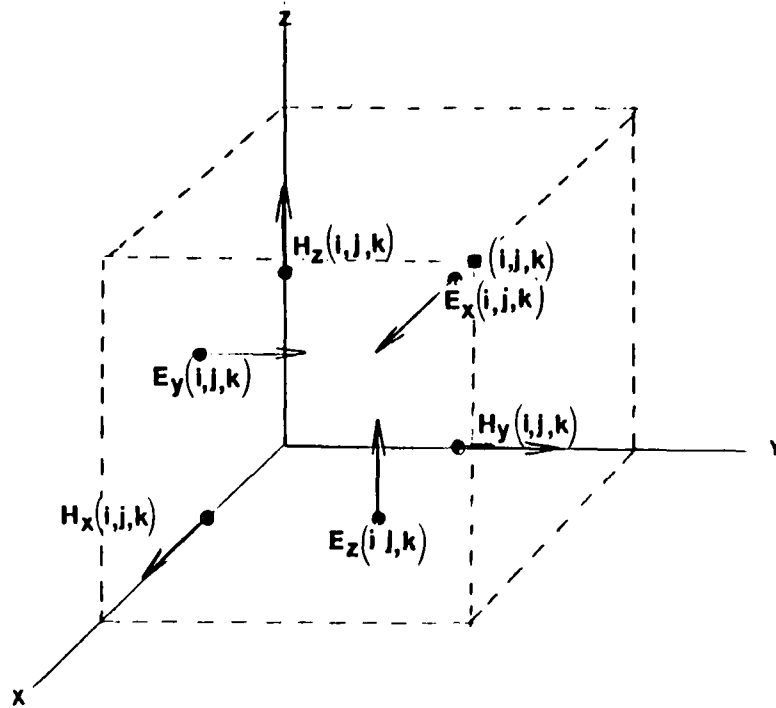
Figure 1.   Three-dimensional Field Representation

Since the computer memory available is a limited
quantity, some boundary must be placed on the problem space
in order to arrive at a meaningful solution.   Each author
has his own style of implementing boundary conditions.   The
two compared in this thesis are often referred to as "soft"
boundary conditions, or "soft" lattice truncation
conditions.   The first to be used is the absorption boundary
condition which Rymes implemented in 3DFD (48).   The second
boundary condition is the radiation boundary condition used
by Kunz (29).

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Finite Difference Form of Maxwell's Equations

The finite difference form of Maxwell's equations uses Eq (2.1) thru Eq (2.4), manipulated in the Cartesian coordinate system, to arrive at a convenient algorithmic form for programming.

In the Cartesian coordinate system, the electric and magnetic *field vectors are as found in Thiele's notation* (53:11):

$$\underline{A} = A_x \, \hat{a}_x + A_y \, \hat{a}_y + A_z \, \hat{a}_z \tag{2.5}$$

where 'A' is equal to the magnitude of the E-field or H-field component and 'a' is the unit vector in the x, y, or z direction.

The curl of A in the Cartesian coordinate system is expressed as follows (24:178):

$$\text{curl } \underline{A} = \nabla \times \underline{A} = \det \begin{vmatrix} \hat{a}_x & \hat{a}_y & \hat{a}_z \\ \dfrac{\partial}{\partial x} & \dfrac{\partial}{\partial y} & \dfrac{\partial}{\partial z} \\ A_x & A_y & A_z \end{vmatrix} \tag{2.6}$$

When the determinant (det) of Eq (2.6) is found, it is

expressed as (59:556):

$$\text{curl } \underline{A} = \left(\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z}\right)\hat{a}_x + \left(\frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x}\right)\hat{a}_y + \left(\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y}\right)\hat{a}_z \quad (2.7)$$

In general, 'A' may also be a function of time.

Substituting E or H for A into Eq (2.7), replacing the curls in Eq (2.1) and Eq (2.2) with the results from Eq (2.7), and lastly separating the vector components yields:

$$\mu \frac{\partial H_x}{\partial t} = -\frac{\partial E_z}{\partial y} + \frac{\partial E_y}{\partial z} \quad (2.8a)$$

$$\mu \frac{\partial H_y}{\partial t} = -\frac{\partial E_x}{\partial z} + \frac{\partial E_z}{\partial x} \quad (2.8b)$$

$$\mu \frac{\partial H_z}{\partial t} = -\frac{\partial E_y}{\partial x} + \frac{\partial E_x}{\partial y} \quad (2.8c)$$

$$\epsilon \frac{\partial E_x}{\partial t} + \sigma E_x = \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} \quad (2.9a)$$

$$\epsilon \frac{\partial E_y}{\partial t} + \sigma E_y = \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} \quad (2.9b)$$

$$\epsilon \frac{\partial E_z}{\partial t} + \sigma E_z = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \quad (2.9c)$$

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These equations are now in a form convenient for use in the algorithm of the finite difference computer code.

The derivatives in Eq (2.8) and Eq (2.9) are replaced by a finite difference approximation. The exact definition of a derivative using forward differencing is (25:289; 7:297):

$$f'(x) = \frac{df(x)}{dx} = \lim_{h \to \emptyset} \frac{f(x+h) - f(x)}{h} \sim \frac{f(x+h) - f(x)}{h} \qquad (2.10)$$

The finite differencing approximation used in this work is the central differencing approximation defined by (7:298):

$$\frac{df(x)}{dx} \sim \frac{f(x+h/2) - f(x-h/2)}{h} \qquad (2.11)$$

and is illustrated graphically in Figure 2.
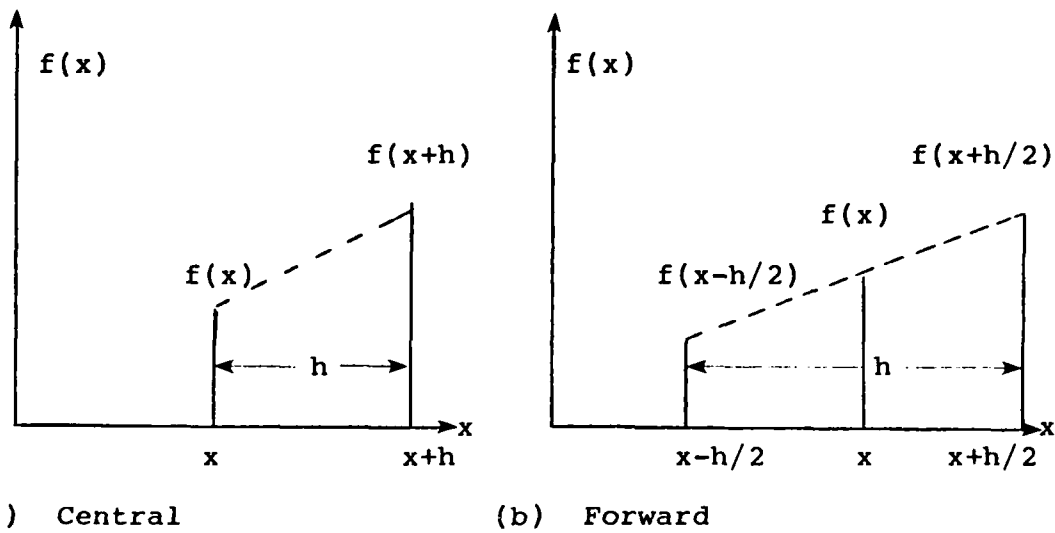
(a)   Central   (b)   Forward

Figure 2.   Differencing Points

By using a Taylor series approximation of Eq (2.11) and Eq (2.12), the errors can be compared (32; 16). The result is that the central differencing approximation is a second order approximation as opposed to forward differencing, which is a first order approximation (32:297, 298). Both of the codes (Appendix A and Appendix B) were run using the central differencing approximations for each derivative.

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Field Locations

The points (i,j,k) which describe the location of the fields in each cell space are reference points on a decentralizing mesh scheme. This decentralizing mesh scheme is best described by first considering the one-dimensional decentralizing mesh (Figure 3). Note that the E-fields and H-fields are not co-located. This displacement keeps one from knowing the E-field and H-field components at the same point in space. The fields are only known at 1/2 the differential distance $(\Delta x/2, \Delta y/2, \Delta z/2)$ in any particular coordinate system direction. Also note that the E-field and H-field are not known at the same time, but that they are separated by 1/2 the time step $(\Delta t/2)$.
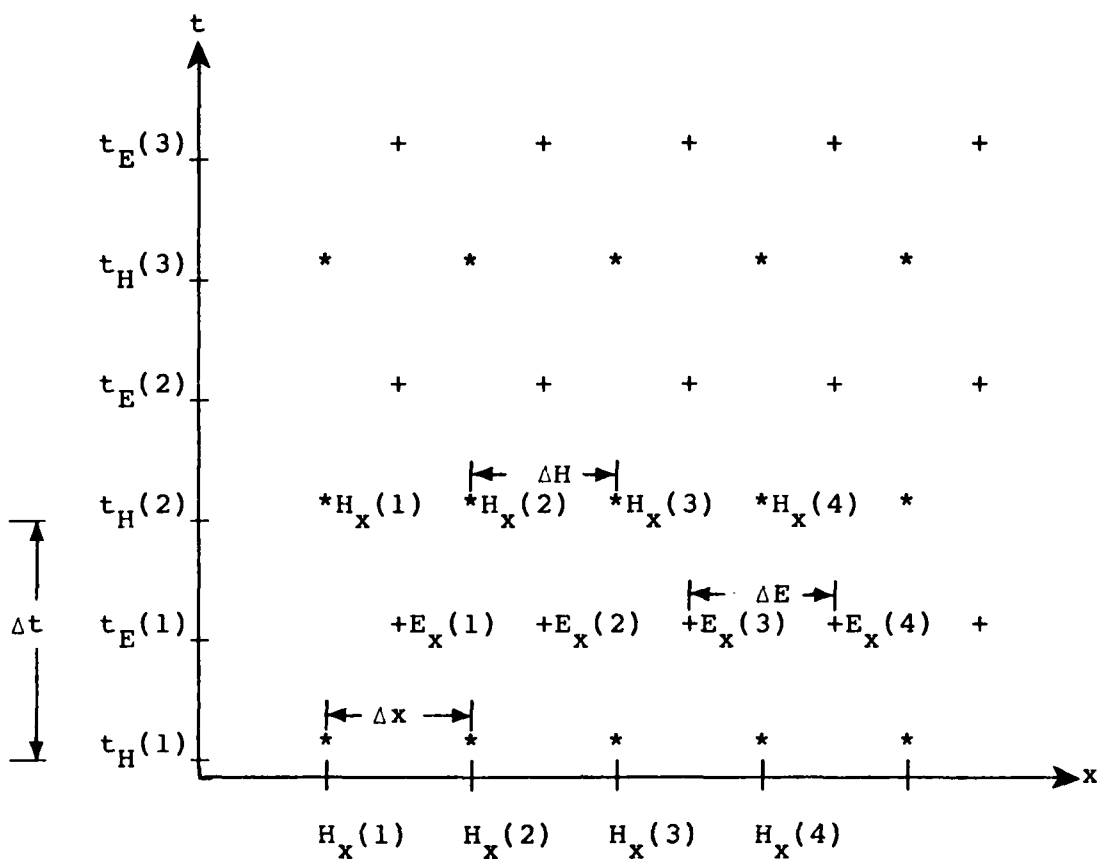
Figure 3. Decentralizing Mesh in One-dimension

To form the derivatives required in Eq (2.8) and Eq (2.9), the dH/dt and dE/dt are needed. As demonstrated graphically in Figure 3, these values are available using this decentralizing mesh concept.

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Three-Dimensional Finite Difference Equations

The Three-Dimensional Finite Difference Equations can be derived by combining the differential form of Maxwell's equations, the definition of curl in the Cartesian coordinate system, and the central differencing approximation to a derivative.

Magnetic-Field Algorithm Development. An example in terms of H_x would combine Eq (2.8a) and Eq (2.11) at a point specified as:

$$\{(i-1/2)\Delta x, j\Delta y, k\Delta z, (n-1/2)\Delta t\}$$

and yield:

$$
\frac{H_x\{(i-1/2)\Delta x, j\Delta y, k\Delta z, n\Delta t\} - H_x\{(i-1/2)\Delta x, j\Delta y, k\Delta z, (n-1)\Delta t\}}{\Delta t}
$$

$$
= \frac{E_y\{(i-1/2)\Delta x, j\Delta y, (k+1/2)\Delta z, (n-1/2)\Delta t\}}{\mu \Delta z}
$$

$$
- \frac{E_y\{(i-1/2)\Delta x, j\Delta y, (k-1/2)\Delta z, (n-1/2)\Delta t\}}{\mu \Delta z}
$$

$$
- \frac{E_z\{(i-1/2)\Delta x, (j+1/2)\Delta y, k\Delta z, (n-1/2)\Delta t\}}{\mu \Delta y}
$$

$$
+ \frac{E_z\{(i-1/2)\Delta x, (j-1/2)\Delta y, k\Delta z, (n-1/2)\Delta t\}}{\mu \Delta y}
$$

$$(2.12)$$

In using this equation, an approximation for H_x can be obtained by knowing E_y and E_z at 1/2 a space increment on

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either side of H_x, at $\Delta t/2$ earlier and H_x one Δt earlier.
Figure 4 illustrates these relationships. Taflove and
Umashankar have shown that this approximation is within the
accuracy of computer calculations (54; 62).
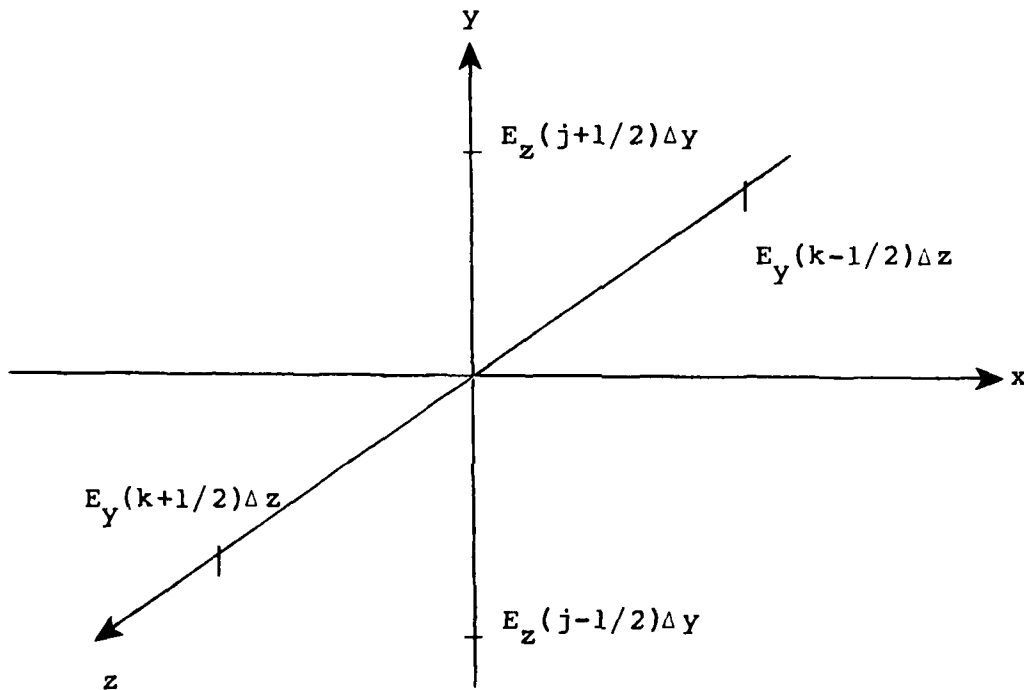
Figure 4. Location of Difference Fields
Note: The origin is centered at
$\{(i-1/2)\Delta x, j\Delta y, k\Delta z\}$, at the time $n\Delta t$.

Next, the E-field can be determined in a similar manner
$\Delta t/2$ later at 1/2 a space increment in the x direction. The
program steps through the decentralizing mesh in half-space
increments and half-time increments until the entire grid
space is covered (NxNxN).

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Similar modifications transform Eq (2.8b) and Eq (2.8c) into

$$\frac{H_y\{i\Delta x,(j-1/2)\Delta y,k\Delta z,n\Delta t\} - H_y\{i\Delta x,(j-1/2)\Delta y,k\Delta z,(n-1)\Delta t\}}{\Delta t}$$

$$= \frac{E_z\{(i+1/2)\Delta x,(j-1/2)\Delta y,k\Delta z,(n-1/2)\Delta t\}}{\mu\Delta x}$$

$$- \frac{E_z\{(i-1/2)\Delta x,(j-1/2)\Delta y,k\Delta z,(n-1/2)\Delta t\}}{\mu\Delta x}$$

$$- \frac{E_x\{i\Delta x,(j-1/2)\Delta y,(k+1/2)\Delta z,(n-1/2)\Delta t\}}{\mu\Delta z} \qquad (2.13)$$

$$+ \frac{E_x\{i\Delta x,(j-1/2)\Delta y,(k-1/2)\Delta z,(n-1/2)\Delta t\}}{\mu\Delta z}$$

at point location $\{i\Delta x,(j-1/2)\Delta y,k\Delta z,(n-1/2)\Delta t\}$ and

$$\frac{H_z\{i\Delta x,j\Delta y,(k-1/2)\Delta z,n\Delta t\} - H_z\{i\Delta x,j\Delta y,(k-1/2)\Delta z,(n-1)\Delta t\}}{\Delta t}$$

$$= \frac{E_x\{i\Delta x,(j+1/2)\Delta y,(k-1/2)\Delta z,(n-1/2)\Delta t\}}{\mu\Delta y}$$

$$- \frac{E_x\{i\Delta x,(j-1/2)\Delta y,(k-1/2)\Delta z,(n-1/2)\Delta t\}}{\mu\Delta y}$$

$$- \frac{E_y\{(i+1/2)\Delta x,j\Delta y,(k-1/2)\Delta z,(n-1/2)\Delta t\}}{\mu\Delta x} \qquad (2.14)$$

$$+ \frac{E_y\{(i-1/2)\Delta x,j\Delta y,(k-1/2)\Delta z,(n-1/2)\Delta t\}}{\mu\Delta x}$$

at point location $\{i\Delta x, j\Delta y, (k-1/2)\Delta z, (n-1/2)\Delta t\}$.

Electric Field Algorithm Development. Operating on the E-field in Eq (2.9a) at grid point

$$\{(i-1)\Delta x, (j-1/2)\Delta y, (k-1/2)\Delta z, n\Delta t\}$$

E_x is first needed at $t = (n+1/2)\Delta t$. Using the average of E_x at $\Delta t/2$, before and after t,

$$E_x(n\Delta t) = \frac{E_x\{(n+1/2)\Delta t\} + E_x\{(n-1/2)\Delta t\}}{2} \tag{2.15}$$

substituting in the space coordinates, one finds

$$E_x\{(i-1)\Delta x, (j-1/2)\Delta y, (k-1/2)\Delta z, n\Delta t\}$$

$$= \frac{E_x\{(i-1)\Delta x, (j-1/2)\Delta y, (k-1/2)\Delta z, (n+1/2)\Delta t\}}{2}$$

$$\tag{2.16}$$

$$+ \frac{E_x\{(i-1)\Delta x, (j-1/2)\Delta y, (k-1/2)\Delta z, (n-1/2)\Delta t\}}{2}$$

and substituting into Eq (2.9a), then expanding the right side as was done in Eq (2.8), the result is

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$$(\epsilon/\Delta t + \sigma/2)(E_x\{(i-1)\Delta x,(j-1/2)\Delta y,(k-1/2)\Delta z,(n+1/2)\Delta t\})$$

$$- (\epsilon/\Delta t - \sigma/2)(E_x\{(i-1)\Delta x,(j-1/2)\Delta y,(k-1/2)\Delta z,(n-1/2)\Delta t\})$$

$$= \frac{H_z\{(i-1)\Delta x,j\Delta y,(k-1/2)\Delta z,n\Delta t\}}{\Delta y}$$

$$- \frac{H_z\{(i-1)\Delta x,(j-1)\Delta y,(k-1/2)\Delta z,n\Delta t\}}{\Delta y}$$

$$- \frac{H_y\{(i-1)\Delta x,(j-1/2)\Delta y,k\Delta z,n\Delta t\}}{\Delta z}$$

$$+ \frac{H_y\{(i-1)\Delta x,(j-1/2)\Delta y,(k-1)\Delta z,n\Delta t\}}{\Delta z}$$

(2.17)

Now sigma, the conductivity, is in the equation. This is the area, that if one were dealing with something other than a perfect conductor, changes in the conductivity could be made. In the data base, one can express the conductivity at each grid point. In the program it is averaged in this manner:

$$\sigma_x = \sigma \{(i-1)\Delta x,(j-1/2)\Delta y,(k-1/2)\Delta z\}$$

(2.18)

$$= \frac{\sigma\{(i-1/2)\Delta x,(j-1/2)\Delta y,(k-1/2)\Delta z\}}{2}$$

$$+ \frac{\sigma\{(i-3/2)\Delta x,(j-3/2)\Delta y,(k-1/2)\Delta z\}}{2}$$

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And epsilon, the permittivity is

$$\varepsilon_x = \varepsilon\{(i-1)\Delta x, (j-1/2)\Delta y, (k-1/2)\Delta z\} \qquad (2.19)$$

Similar operations for E_y at

$$\{(i-1/2)\Delta x, (j-1)\Delta y, (k-1/2)\Delta z, n\Delta t\}$$

yields

$$(\varepsilon/\Delta t + \sigma/2)(E_y\{(i-1/2)\Delta x, (j-1)\Delta y, (k-1/2)\Delta z, (n+1/2)\Delta t\})$$

$$- (\varepsilon/\Delta t - \sigma/2)(E_y\{(i-1/2)\Delta x, (j-1)\Delta y, (k-1/2)\Delta z, (n-1/2)\Delta t\})$$

$$= \frac{H_x\{(i-1/2)\Delta x, (j-1)\Delta y, k\Delta z, n\Delta t\}}{\Delta z}$$

$$- \frac{H_x\{(i-1/2)\Delta x, (j-1)\Delta y, (k-1)\Delta z, n\Delta t\}}{\Delta z}$$

$$- \frac{H_z\{i\Delta x, (j-1)\Delta y, (k-1/2)\Delta z, n\Delta t\}}{\Delta x} \qquad (2.20)$$

$$+ \frac{H_z\{(i-1)\Delta x, (j-1)\Delta y, (k-1/2)\Delta z, n\Delta t\}}{\Delta x}$$

and for E_z at $\{(i-1/2)\Delta x, (j-1/2)\Delta y, (k-1)\Delta z, n\Delta t\}$

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$$(\epsilon/\Delta t + \sigma/2)(E_z\{(i-1/2)\Delta x, (j-1/2)\Delta y, (k-1)\Delta z, (n+1/2)\Delta t\})$$

$$- (\epsilon/\Delta t - \sigma/2)(E_z\{(i-1/2)\Delta x, (j-1/2)\Delta y, (k-1)\Delta z, (n-1/2)\Delta t\})$$

$$= \frac{H_y\{i\Delta x, (j-1/2)\Delta y, (k-1)\Delta z, n\Delta t\}}{\Delta x}$$

$$- \frac{H_y\{(i-1)\Delta x, (j-1/2)\Delta y, (k-1)\Delta z, n\Delta t\}}{\Delta x}$$

$$- \frac{H_x\{(i-1/2)\Delta x, j\Delta y, (k-1)\Delta z, n\Delta t\}}{\Delta y} \qquad (2.21)$$

$$+ \frac{H_x\{(i-1/2)\Delta x, (j-1)\Delta y, (k-1)\Delta z, n\Delta t\}}{\Delta y}$$

Finally, in rearranging the electric field equation and the magnetic field equation, one arrives at a form which is useful in understanding the relationship between various fields and the code. For example:

$$H_x\{i,j,k,n\Delta t\} = H_x\{i,j,k,(n-1)\Delta t\}$$

$$+ \left(\frac{\Delta t}{\mu}\right)\left(\frac{E_y\{i,j,(k+1/2),(n-1/2)\Delta t\}}{\Delta z}\right.$$

$$- \frac{E_y\{i,j,(k-1/2),(n-1/2)\Delta t\}}{\Delta z}$$

$$- \frac{E_z\{i,(j+1/2),k,(n-1/2)\Delta t\}}{\Delta y} \qquad (2.22)$$

$$+ \left.\frac{E_z\{i,(j-1/2),k,(n-1/2)\Delta t\}}{\Delta y}\right)$$

and

$$E_x\{i,j,k,(n+1/2)\Delta t\} = E_x\{i,j,k,(n-1/2)\Delta t\}\left(\frac{\epsilon/\Delta t - \sigma/2}{\epsilon/\Delta t + \sigma/2}\right)$$

$$+ \left(\frac{1}{(\epsilon/\Delta t + \sigma/2)}\right)\left(\frac{H_z\{i,(j+1/2),k,n\Delta t\}}{\Delta y}\right.$$

$$- \frac{H_z\{i,(j-1/2),k,n\Delta t\}}{\Delta y}$$

$$\hspace{6cm}(2.23)$$

$$- \frac{H_y\{i,j,(k+1/2),n\Delta t\}}{\Delta z}$$

$$\left.+ \frac{H_y\{i,j,(k-1/2),n\Delta t\}}{\Delta z}\right)$$

In this manner, the E_x can be calculated knowing the H-field $\Delta t/2$ earlier at the four adjacent points in the orthogonal plane, $\Delta y/2$ and $\Delta z/2$ away, and the E_x $\Delta t/2$ earlier at the same point. A similar statement can be made about H_x, Eq (2.23).

Thus, at every time step ($\Delta t/2$), a complete set of either E or H fields is calculated for the entire problem space. This process is continued in time until a steady state response is reached.

For computational stability, Δt must satisfy the Courant stability condition (27:329; 64:303),

$$\Delta t < \frac{1}{V_{max}(\Delta x^{-2} + \Delta y^{-2} + \Delta z^{-2})^{1/2}} \qquad (2.24)$$

where V_{max} is the maximum velocity of propagation in the medium. Eq.(2.24) means that the increment of the time steps must be smaller than the time it takes the wave to travel. This keeps the magnitude of the field finite differences small, so that the solution is stable. In other words, the finite differences are small because the passage of time was small enough to allow only small changes in magnitudes.

3. Boundary Conditions

Boundary conditions are necessary because space in general is infinite, but the computer has to have a finite number of values to make its calculations. An infinite space is simulated by truncating the problem space with carefully chosen boundary conditions. Examining Eq (2.22) and (2.23), it can be shown (as in Hebert's development of the propagation in one direction) that some type of boundary condition is absolutely necessary for the finite difference code (16). Without boundary conditions, the fields at the problem space boundary would be undefined and would not allow the calculation of the next field when stepping through the space. The end result is a decreasing data base of past fields from which to calculate the subsequent solutions.

There are numerous boundary conditions imposed by different authors in the algorithms of the finite difference codes. The first author that developed the finite difference algorithm, Yee, simply forced the outer problem space boundary to be a perfect conductor (64). This causes 'noise' in the solution, due to the reflections off the boundary (55:626). Others use a combination of Yee's, "hard" boundary conditions and "soft" ones, which reduce the reflection problem (55:626). The two "soft" boundary conditions considered are the absorption and the radiation boundary conditions.

Absorption Boundary Condition

The conductivity of the problem space is set to zero in
the center, but at the outer edges it is set to some small
value, such as that of distilled water (Figure 5). This has
the effect of "absorbing" the fields to the point that the
reflected waves from the outermost boundary will not perturb
the solution of the fields in the center of the problem
space.

```
                        |
   .    σ = 0    .       |    σ = 10⁻⁴ .
                        |
-----------+----------+-----|----+----------+----
                        |
   .         .         .  |    .          .
                        |
   +         +         +  |    +          +
                        |
   .    σ = 10⁻⁴.        |    σ = 10⁻⁴ .
                        |
   +         +         +  |    +          +
                        |
```
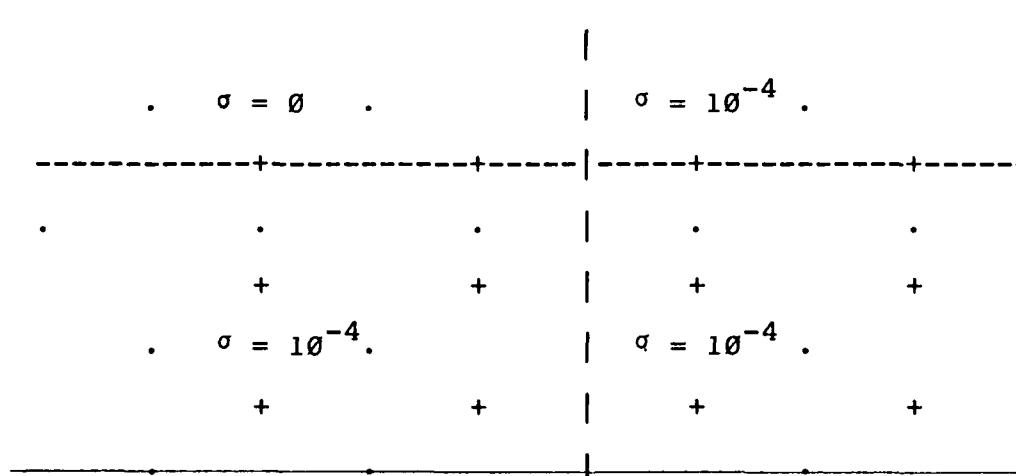
Figure 5. Finite Conductivity at Boundary Edges

This absorption boundary condition requires approximately
one wavelength's distance to the boundary to simulate a low
reflectivity surface (55:626). This additional size added
onto the problem space greatly increases the computer memory

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and time for calculations (55:626). This particular

boundary condition was used in Rymes' code (48).

Radiation Boundary Condition

The radiation boundary condition uses a far-field

approximation and the radiation condition to emulate an

ideal infinite problem space. The general form of the

radiation condition was originally introduced by Merewether

(38:41). Bayless and Turkel have shown that the radiation

boundary condition is a very valid mathematical technique

(4). The form of the radiation boundary condition is: some

function of time f(t-r/c) divided by radial distance, r,

from the center of the problem space (38:41).

$$E = \frac{f(t-r/c)}{r} \tag{3.1}$$

where

f = causal vector function
t = time
c = speed of light
r = large distance from the center of the test object

The function, 'f', used by Merewether will be the one

incorporated into the modified Rymes' code (38:42). The

fields at the boundary are found by parabolic interpolation

in time, of the fields that are one cell in from the outer
boundary, at $n\Delta t$, $(n-1)\Delta t$ and $(n+1)\Delta t$. This is expressed as
E_z at the outer boundary point (i,j,k), maximum j-plane
boundary, in the y-direction as:

$$E_z^{n+1}(i,j,k) = \frac{R_z(i,j-1,k)}{2R_z(i,j,k)} \, f\{\Theta,E(t)\} \qquad (3.2)$$

where

$$f\{\Theta,E(t)\} = \Theta_{zy}(\Theta_{zy} - 1)E_z^{n-1}(i,j-1,k)$$

$$+ 2(1 - \Theta_{zy}^2)E_z^n(i,j-1,k)$$

$$+ \Theta_{zy}(\Theta_{zy} + 1)E_z^{n+1}(i,j-1,k)$$

$$R_z(i,j,k) = \{x(i)^2+y(j)^2+z(k)^2\}^{1/2}$$

$$\Theta_{zy} = 1 - \frac{R_z(i,j,k) - R_z(i,j-1,k)}{c\Delta t}$$

and the x,y,z position coordinates for the outer boundaries
are such that the coordinate system's origin is in the
center of the problem space. The 'c' here is taken to be
the speed of light in free space, and Δt is the time elapsed
since last grid position. Similarly, E_x can be expressed
for this boundary. Two components, for each of the
remaining five sides of the problem space, are also
expressed in the same way. Eq (3.2) works for a constant

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cell size problem space. More elaborate expressions are required for an expanding cell size grid (20:2419).

Implementing Eq.(3.2) into code turned out to be a major task. In fact, half the time spent on this thesis was devoted to simply understanding this radiation boundary condition. Researching the radiation boundary condition's origin, and then implementing it into the 3DFD computer code, was a much larger task than originally estimated. References were not found which specifically covered a non-uniform problem space. A non-uniform problem space in this text is one with three different size sides to each element's rectangular box. A major clue was found in a report by Merewether and Fisher (39:74). Looking at Eq.(3.2), the expression for Θ contains a '1' and a $c\Delta t$. The expression directly coded into FORTRAN gave disastrous results.

This direct programing caused the calculated field magnitudes to blow up. In looking into the problem, it became obvious that $c\Delta t$ had to be different for each direction considered. This was taken care of by realizing that $c\Delta t$ was the distance traveled in the increment of time in a particular direction. This could simply be replaced by the space increment dimension over which the derivative was being considered. Note that the '1' now needs to represent an integer one higher than the quantity being subtracted away in the expression for Θ (7:120). If this last

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precaution is not taken, the sign of Θ varies and the parabolic interpolation is incorrect. Detailed expressions can be found in Appendix B.

A smoother waveform is the expected result when using the radiation boundary conditions instead of the absorption boundary conditions. The reflected waves which are caused by the discontinuities at the changes in problem space conductivity, are expected to be reduced. Because of this, the interaction of the reflected waves should be greatly reduced or eliminated. In general, the reflective waves can be thought of as destructive and constructive interference of the output/resulting waveform. This interference is believed to be the cause of the abnormal magnitude variations. Therefore, reducing this destructive and constructive interference caused by the reflected waves should result in a smoother-appearing output waveform.

4. Modeling the F-16

The F-16 'Fighting Falcon' was chosen as the aircraft to be modeled in this thesis. The F-16 was chosen because of the current lightning susceptibility testing being conducted. The thesis sponsor, AFWAL/FIESL, was performing lightning strike tests on the new LANTIRN navigation pod installed on a F-16 (9). Another reason for the choice of the F-16 was due to its being the first operational fighter with a "fly-by-wire" flight control system. The high interest in the survivability of the "fly-by-wire" system after a lightning strike caused many studies to be performed, supplemented with many on-going efforts to protect this system (6). A large data base was therefore available for follow-on comparisons and studies. First, the problem space will be described in general. Then the choices which were made to model the F-16 in the time-domain finite difference problem space, will be explained. The last area to be covered will be the location of the ten sample points.

Problem Space

The problem space is made up of a rectangular area subdivided into 19,683 rectangular cells. The positions within this problem space are defined in terms of the Cartesian coordinate system. This particular choice of coordinate systems is well-suited to the finite difference formulation previously mentioned. The space is divided into rectangular grids referenced by integers such as $(i,j,k)=(1,1,1)$. The particular length of each grid is chosen to enhance the description of the geometry of the subject object. Each of the three directions is divided into the same number of grids, although this is not required. The best way to describe this is by an example. The program used for this thesis incorporates a 27X27X27 (=19,683) grid space. In meters, the x-direction increment is 0.69 meters, y-direction is 0.22 meters, and the z-direction is 0.45 meters (Figure 6). Since the grids remain a uniform size in a given direction, this makes the overall physical size of the grid space 18.63, 5.94, and 12.15 meters respectively, in the x,y,z directions.
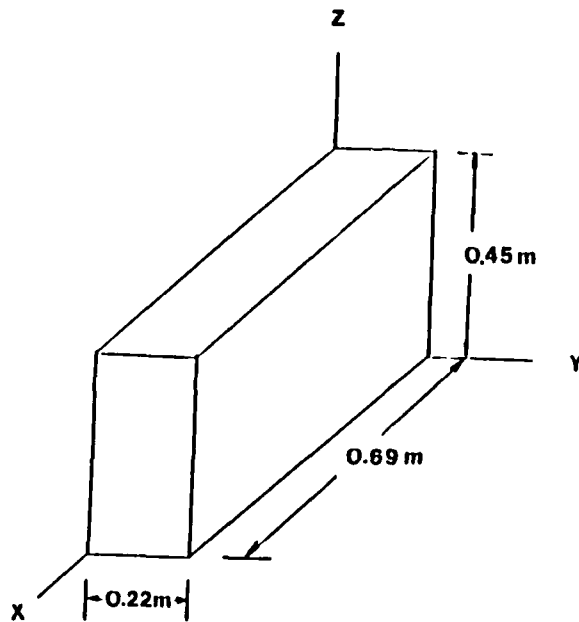
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Figure 6. Basic Grid Block

The constraint of memory size and processing time are
the main limiting factors for the number of grid divisions
used (e.g., 27X27X27). Each of the 19,683 grid points has
six fields associated with it. After one complete run of
the program through the problem space, 118,098 fields have
been calculated. This run through the problem space occurs
at every time increment ($\Delta t/2$). The time step in this
thesis was 0.366667 nanoseconds. A valid run may include up
to two microseconds of data. More time results in large
numerical errors (13:50). Two microseconds corresponds to
5455 complete cycles through the problem space. Clearly,
this is already amounting to large amounts of memory and

central processor (CPU) time. When the amount of
calculations per cycle is considered, the problem becomes
evident.

The finest detail needed to be represented on the model
determines the increment size in each direction. Complete
descriptions can be found on the problem space in most
finite difference users' manuals (18; 2Ø; 29; 48; 6Ø).
These same users' manuals will contain information on
implementing the most efficient dimensions for the problem
space and element blocks. The 27 cubed problem space was
used in comparing both the radiation and absorption boundary
conditions. The aircraft was allowed to take up a large
portion of the problem space.

The remainder of the problem space left a minimal
number of rectangular blocks beyond the aircraft dimensions.
The blocks outside the aircraft's dimensions are used for
the boundary conditions. Using a minimum number of blocks
is not a good practice in general, but was intentionally
done to exercise the boundary conditions under a worst case
scenario. In particular, only three blocks were used to
implement the boundary conditions. The aircraft's maximum
dimensions were extended into an aircraft grid space
21X21X21, centered in the 27X27X27 problem space. This
leaves the 6 blocks (3 on each face of the box) in each
direction for use in implementing the boundary conditions.

Field Locations

Each corner of a rectangular box in the problem space defines a set of fields (Figure 7). The 6 fields described are the 3 electric fields and the 3 magnetic fields in each vector direction. The fields are only defined by these points; they are not actually located there. The E-fields defined by point (i,j,k) are perpendicular and centered on the three sides of the rectangular box, not touching the defining point. The H-fields lie on the edges of these same sides most distant from the defining point. The directional nature of these 6 fields is as established by the coordinate system used (Figure 7).
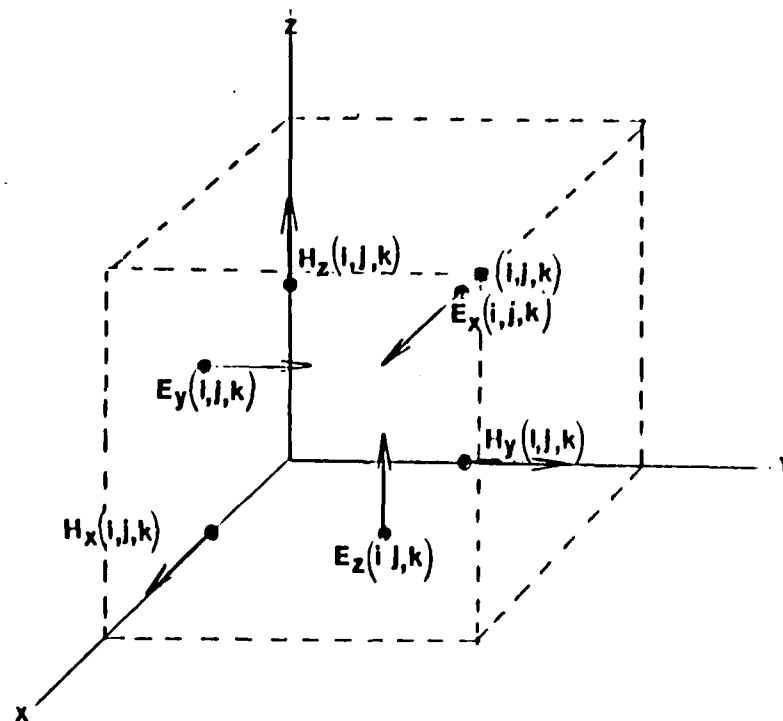

Figure 7. Field Locations with the Decentralizing Grid
System

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Cell Size Choices Made for the F-16

The F-16 is a very smooth, aerodynamically designed
aircraft. This aerodynamic design consists of many curved
surfaces (Figure 8). These curved surfaces presented a
challenge to model with the rectangular blocks of the
Cartesian coordinate system in the problem space. The F-16
has an overall length of 15.09 meters, width of 9.45 meters,
and a height of 4.6 meters (Figure 8) (9:FO-3). The x
coordinate is associated with the length of the aircraft
(Figure 9). The x direction increment of 0.69 meters was
chosen as a compromise to better model the geometrical
structure of the wings in the xz plane (Figure 9). The y
coordinate is associated with the height of the aircraft
(Figure 10). The y direction increment of 0.22 meters was
selected primarily to model the wing root area of the F-16
(Figure 10). The z coordinate is associated with the width
of the aircraft (Figure 11). The z direction increment of
0.45 meters was chosen to model the detail of the speed
brake and the base of the vertical stabilizer. The result of
these choices was a good geometrical model which matches the
F-16's predominant details (Figure 12).

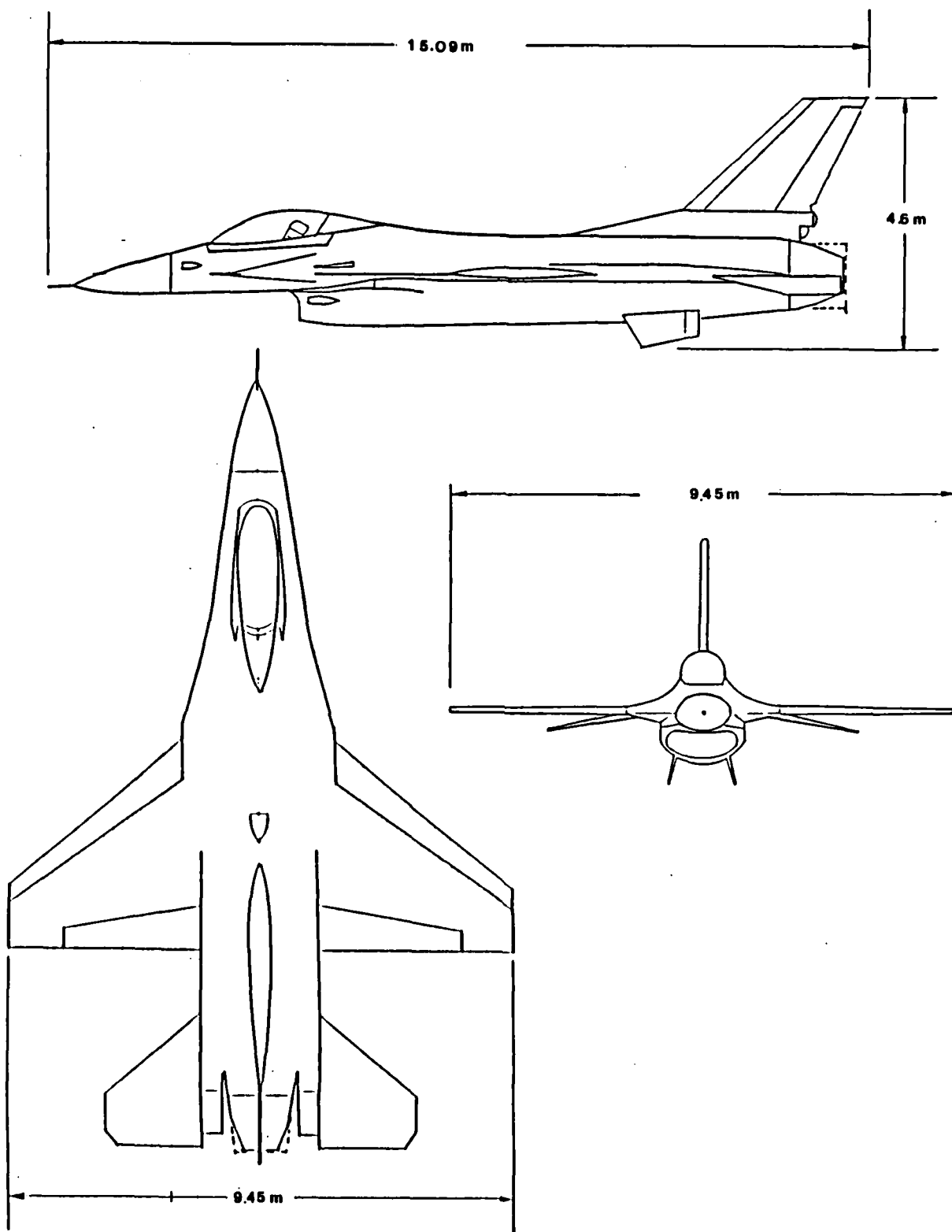Figure 8. F-16 Fighting Falcon
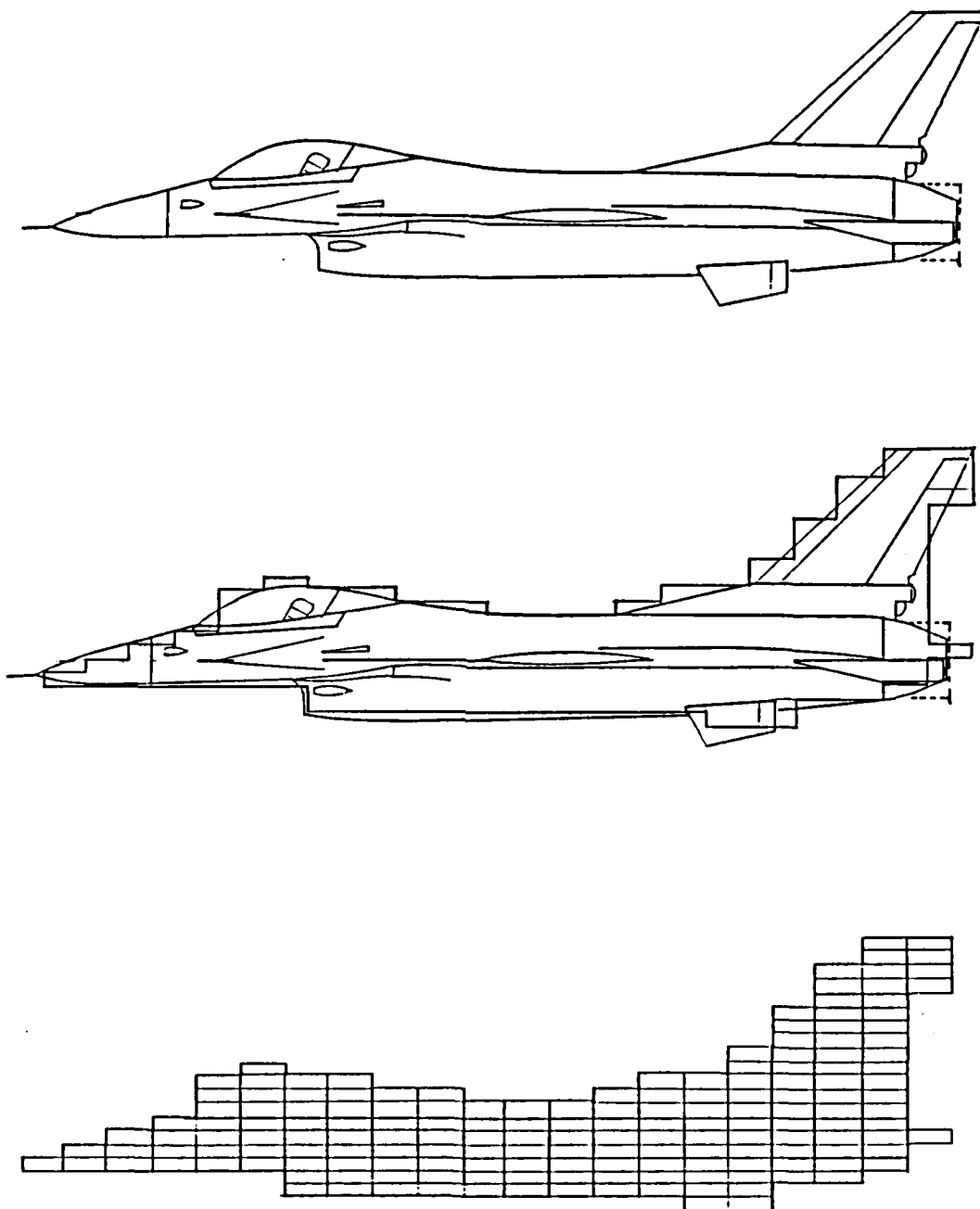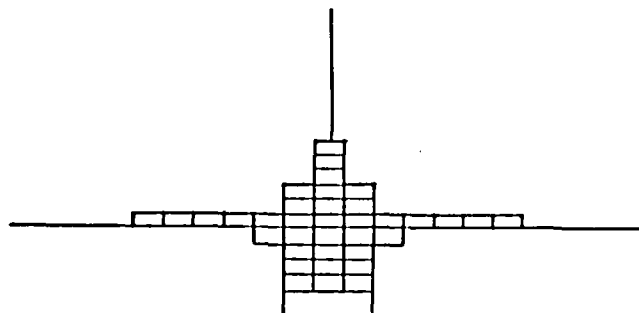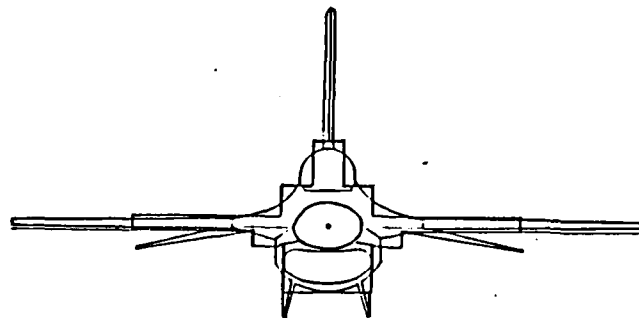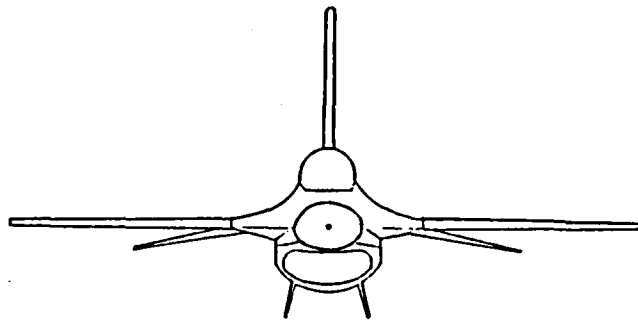
Figure 9.   Gridding of the F-16, Side View

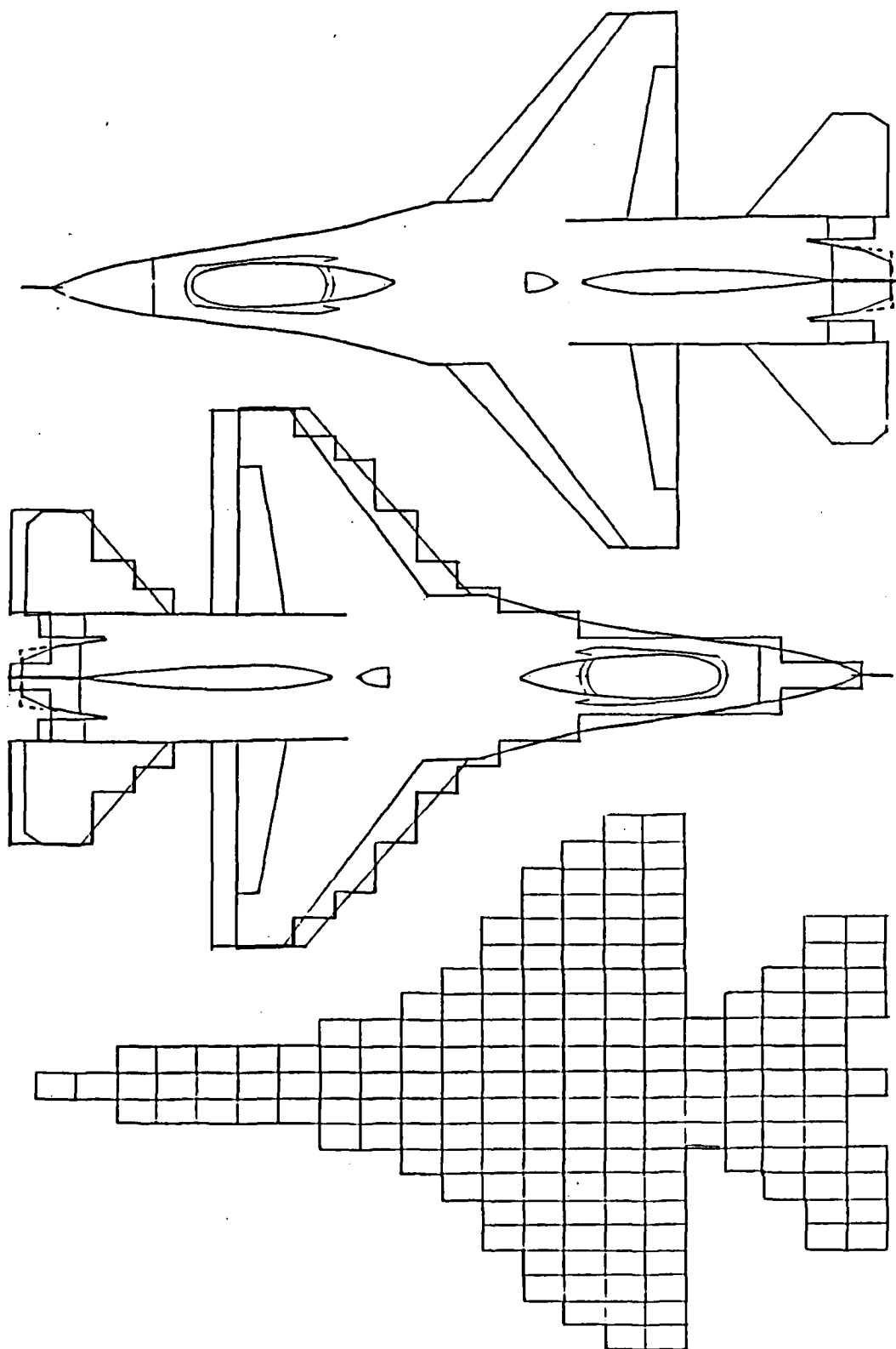Figure 10. Gridding of the F-16, Front View

Figure 11. Gridding of the F-16, Top View
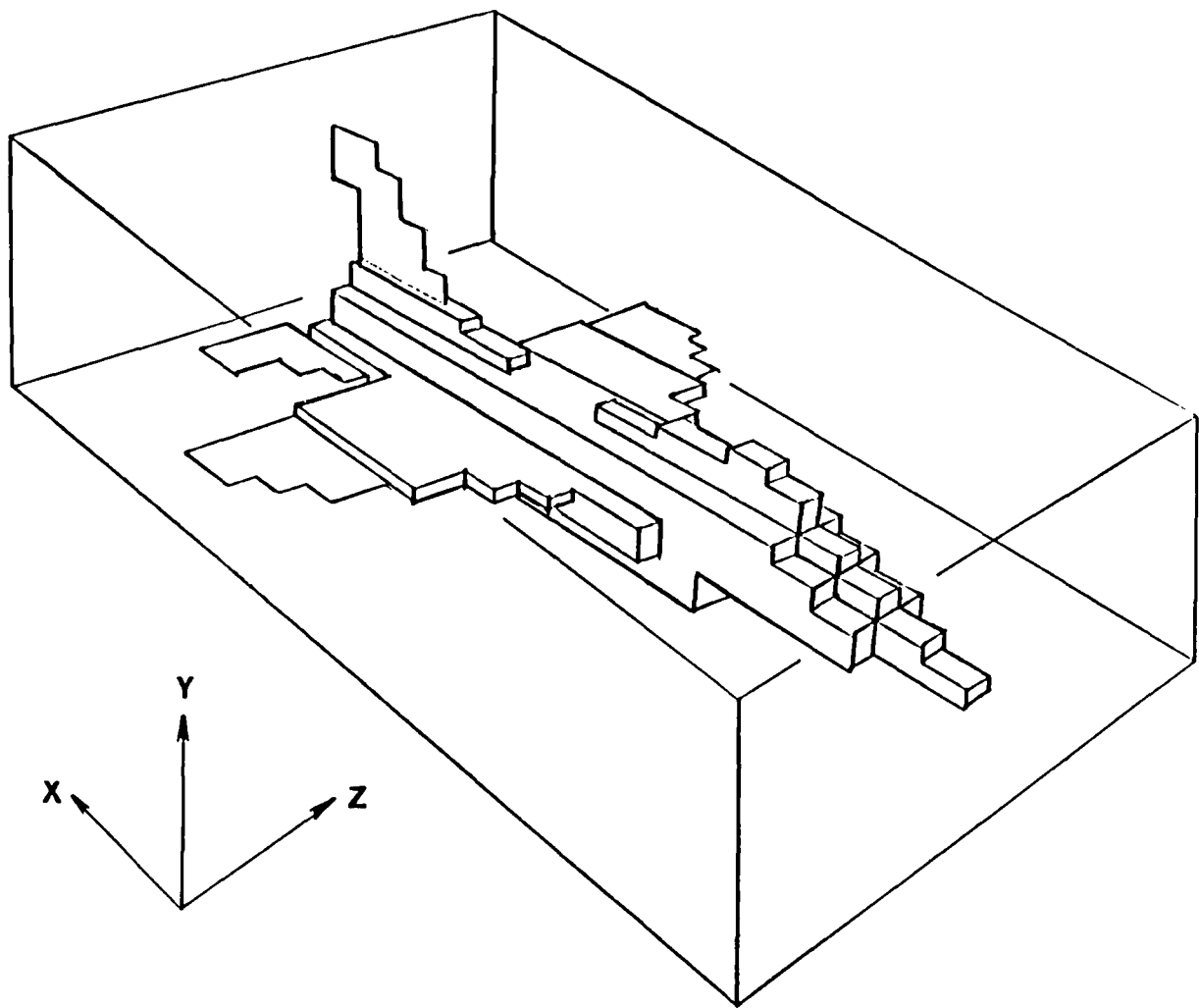
Figure 12.   Three-dimensional Drawing of F-16 as Blocks

The aircraft is described to the computer in subroutine 'AIRPLN' (Appendix A). The description of the geometry of the aircraft is accomplished by defining the tangential E-

fields of the surfaces. The building of the model (Figure

13) was an extremely important step in defining the location

of the tangential surface fields. Each field must be

assigned by grid space location and magnitude. The

tangential surface E-fields, surface normal H-fields and all

interior fields are set equal to zero in the case of a

perfectly conducting surface. Refer to Appendixes A and B

for listings of all of the computer codes used, including

the subroutine AIRPLN. A useful device for detailing the

field locations was a clear plexiglas cube, with the field

locations accordingly marked such as Figure 1. Another

technique used in modeling the F-16 was to take the wood and

metal model and position the xz-planes, or layers, of the

mock-up on a scaled grid plane. This enabled actually

seeing where the fields were physically located. The coding

of the subroutine AIRPLN and understanding the field

locations was greatly simplified with this technique.
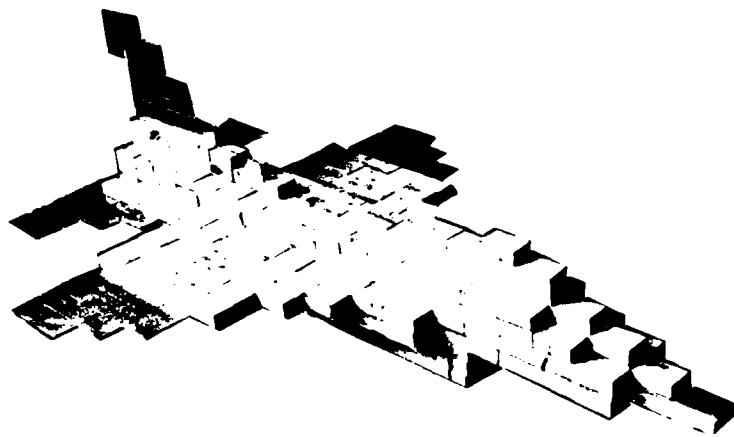
(a) Top View
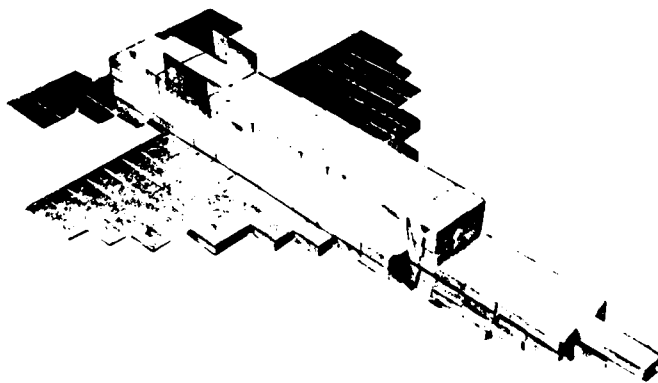
(b) Bottom View

Figure 13.   Photograph of F-16 Block Model

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5. Program Details

The modified Rymes' code was reviewed in great detail. Some changes were made to the modified code before running the F-16 with the absorption boundary conditions. The code was then modified to include the radiation boundary conditions. The sensor locations were selected and encoded in subroutines 'EADV' and 'HADV'. Lastly, the source was updated to reflect parameters recently measured in flight (8; 17; 47; 49).

Basic Code

The assumptions made about the modified Rymes' 3DFD code were basically sound. In reviewing the modified code, only a few minor omissions and corrections were made. The results after complete computer runs on the F-16 model were as expected. The changes made to the modified code with the absorption boundary conditions enhanced the results (Appendix C). A completely updated and corrected copy of the code is in Appendix A.

Boundary Conditions

After running the code with the absorption boundary condition, the radiation boundary condition was implemented. The specific listing can be found in Appendix B, subroutine 'RADBC' and 'HADV'. A significant amount of time was spent in transforming the rather simple-appearing parabolic interpolation of (Eq 3.2) into Fortran 77 code. The basic problem was caused by a lack of details in the literature. The missing details were definitions of time increments in relation to the three different dimensions of the basic problem space block (Figure 6). In particular, the calculation of 'θ' is very sensitive to the definition of $c\Delta t$ (Eq 3.2).

Sample Point Locations

Ten locations were selected as typical for field sensor layouts on the aircraft. Similar locations were used in a CV-580 flight test conducted by AFWAL (16). Any of the three orientations of either the E-field or the H-field could have been selected at any point in the problem space for monitoring. The selections made are detailed in Table 1.

TABLE 1. Ten Sampled Points

Sensor #	Type H or E	Location Description	Direction Component	Coordinates (i,j,k)
1	H-field	right wing	x	(18,10,6)
2	H-field	nose	z	(4,10,13)
3	H-field	engine feathers	z	(24,11,13)
4	H-field	bottom fuselage	z	(10,4,14)
5	H-field	bottom fuselage	z	(19,4,14)
6	H-field	vertical stab	x	(22,18,14)
7	H-field	left wing	x	(18,10,23)
8	E-field	right wing	y	(17,11,10)
9	E-field	top fuselage	y	(15,13,14)
10	E-field	left wing	y	(17,11,18)

The sensor locations are shown in Figure 14. Appendix A, subroutine 'EADV' and 'HADV' show the code used to sample these points at each time step. This sampling will be found under 'sample points of interest' at the end of both subroutines.

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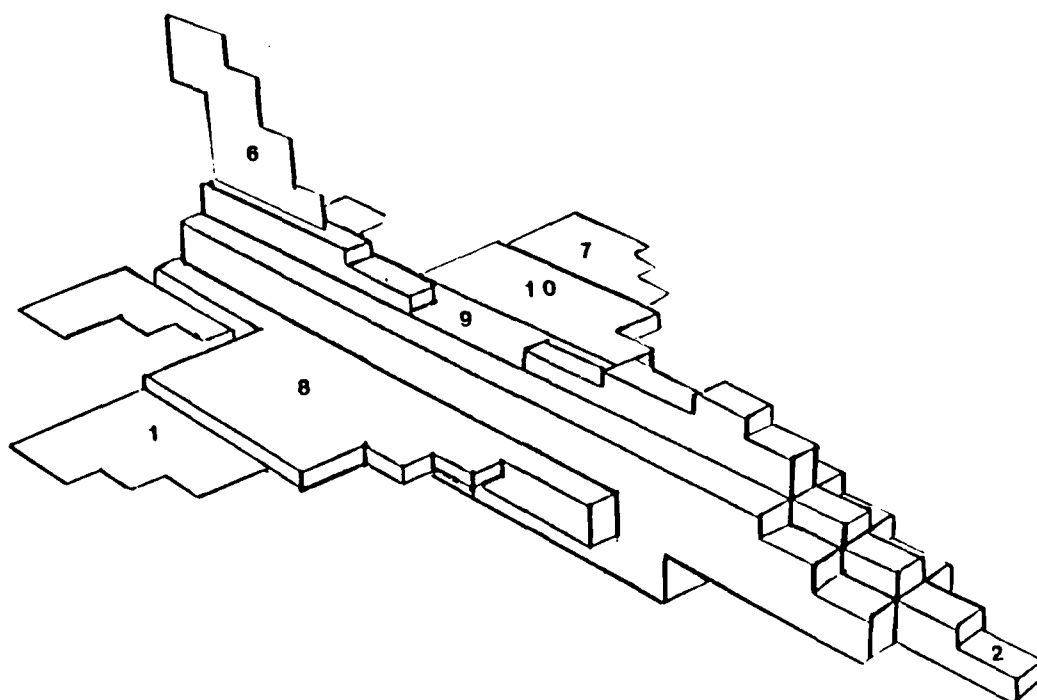
(a) Top View
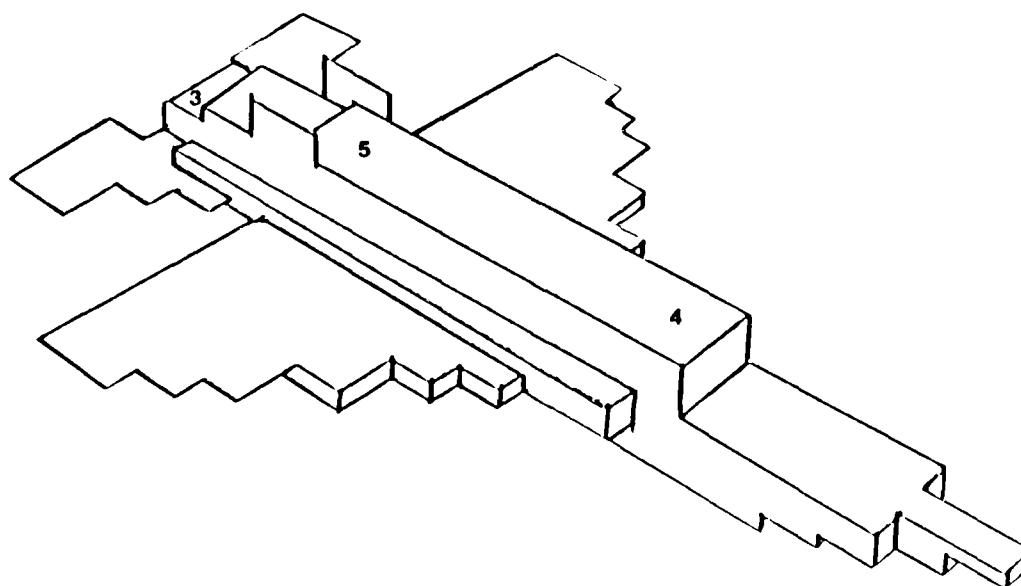
(b) Bottom View

Figure 14. Sensor Locations on a Block F-16 Model

Source Function

A couple of the changes made to the code were in the source function. The "transparent" source function utilized in the modified Rymes' code caused some unnatural growth in the response (19). The so-called "transparent" source added the scattered fields to the source fields, resulting in an ever-increasing source function. Modifications made in the code appearing in Appendix A corrected this growth and gave much better results. The risetime (10% to 90% of the maximum amplitude) was changed to 100 nanoseconds (Figure 15). This was found, by AFWAL measurements, to be more characteristic of cloud-to-cloud lightning strikes (8:128). The normalized source function is plotted in Figure 16 out to the 50% falloff point, which occurs at 20.4 microseconds.

Numerous programs, or researchers, use this double exponential as the source function, which is sometimes called the 'Bruce-Golde' model (8:36). This source function emulates a lightning strike's characteristic waveform (19). The source is attached to the aircraft with a surface current injection technique, as described by Kunz (30:1423). This surface current injection technique is basically accomplished by inserting an H-field into the grid space boundary conditions. The insertion of the H-field takes place around the point that the lightning attachment is being simulated. The H-field is approximated from the

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relationship, H = I/(2 r); where 'I' is the time-varying, analytical current model for the lightning channel desired, and 'r' is the radial distance from the point of desired injection to the nearest H-fields surrounding that point (24:165).
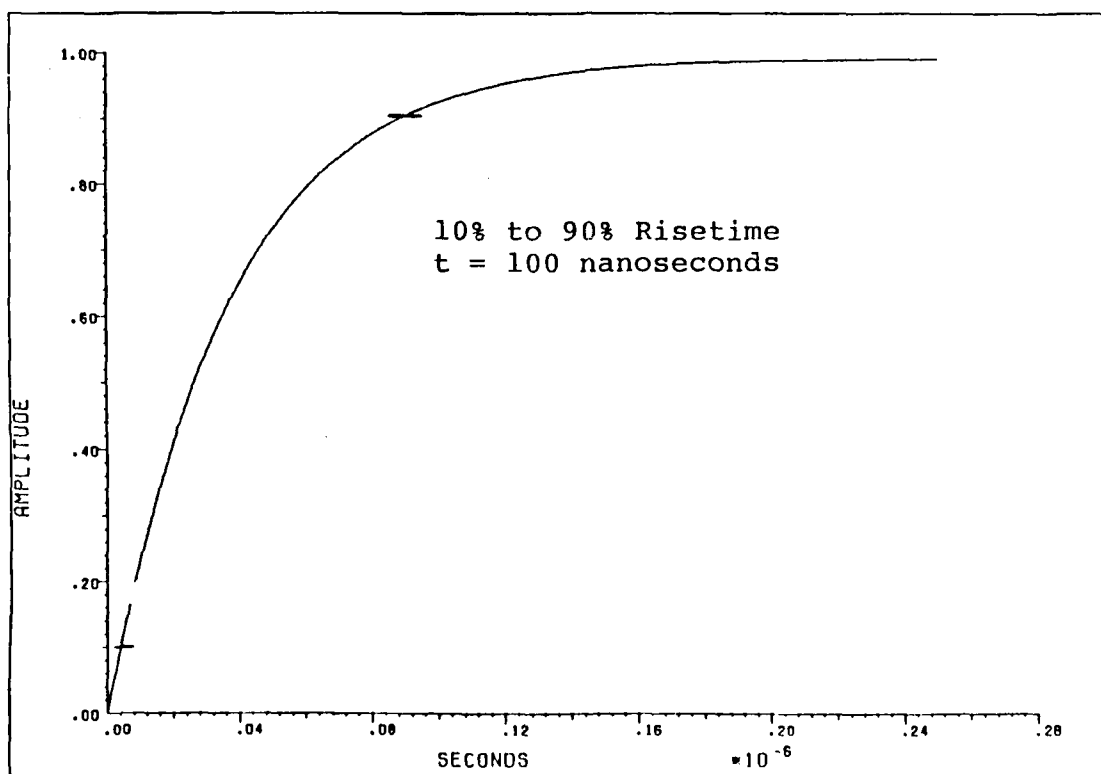

Figure 15. Expanded Plot of Source (First 250 nanoseconds)
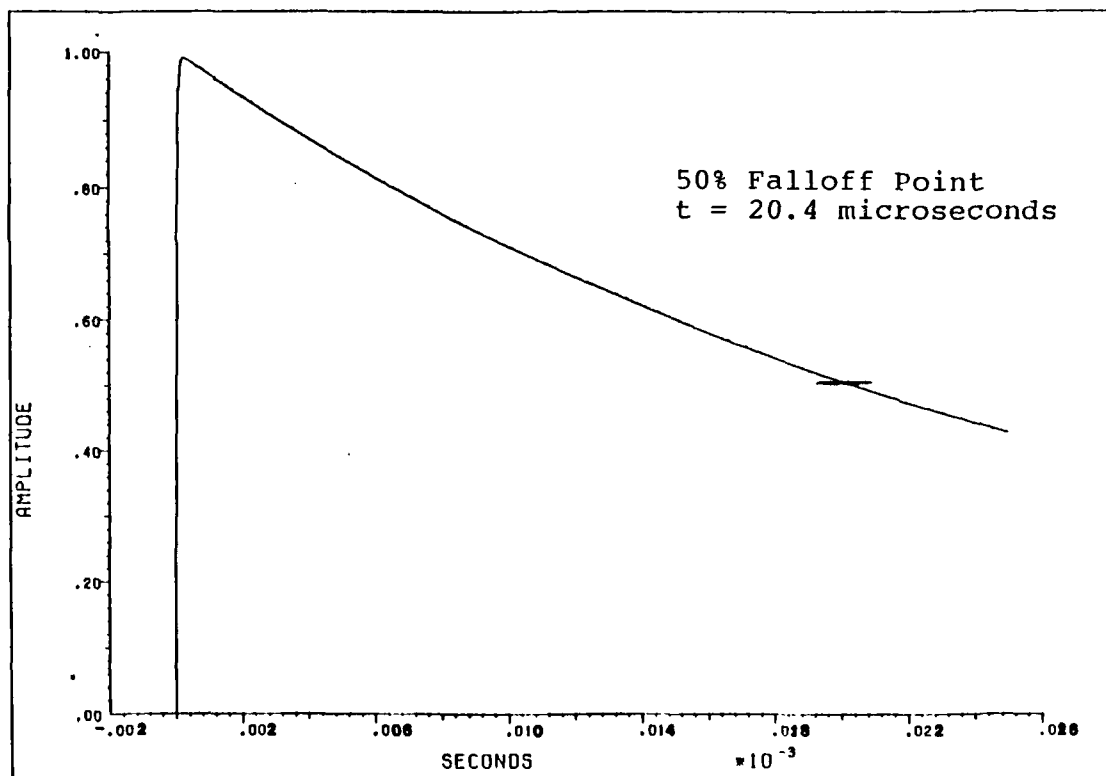
Figure 16.   Normalized Double Exponential Source Function

6. Analysis

The result of implementing the radiation boundary conditions appears to be an improvement over the absorption boundary conditions results. The absorption boundary condition results contain many fluctuations in amplitude that can be attributed to the boundary conditions (19; 55). When the waves travel and hit the discontinuity at the element rectangular cells which have increased conductivity, they reflect back with a discrete magnitude. These reflected waves cause the additional amplitude fluctuations not found with the radiation boundary condition. All ten sensors showed the same results: a general smoothing of the amplitude of the response on the aircraft's skin (Appendix C). All the field plots (Appendix C) had the same basic shape before and after the boundary conditions were changed. The first 300 nanoseconds of each fields response are plotted in this chapter (Figure 17 thru Figure 26). Each sensor's response is plotted on the same graph for both absorption boundary conditions and radiation boundary conditions. The absorption boundary condition plots are annotated with an '*'. The smoother response of the radiation boundary condition resembles the MIE solutions as calculated by Holland (20:206). Note that the disparity in the polarity of the E-field response (sensor 8 & 10) was possibly caused by a resonance effect in the wing region.

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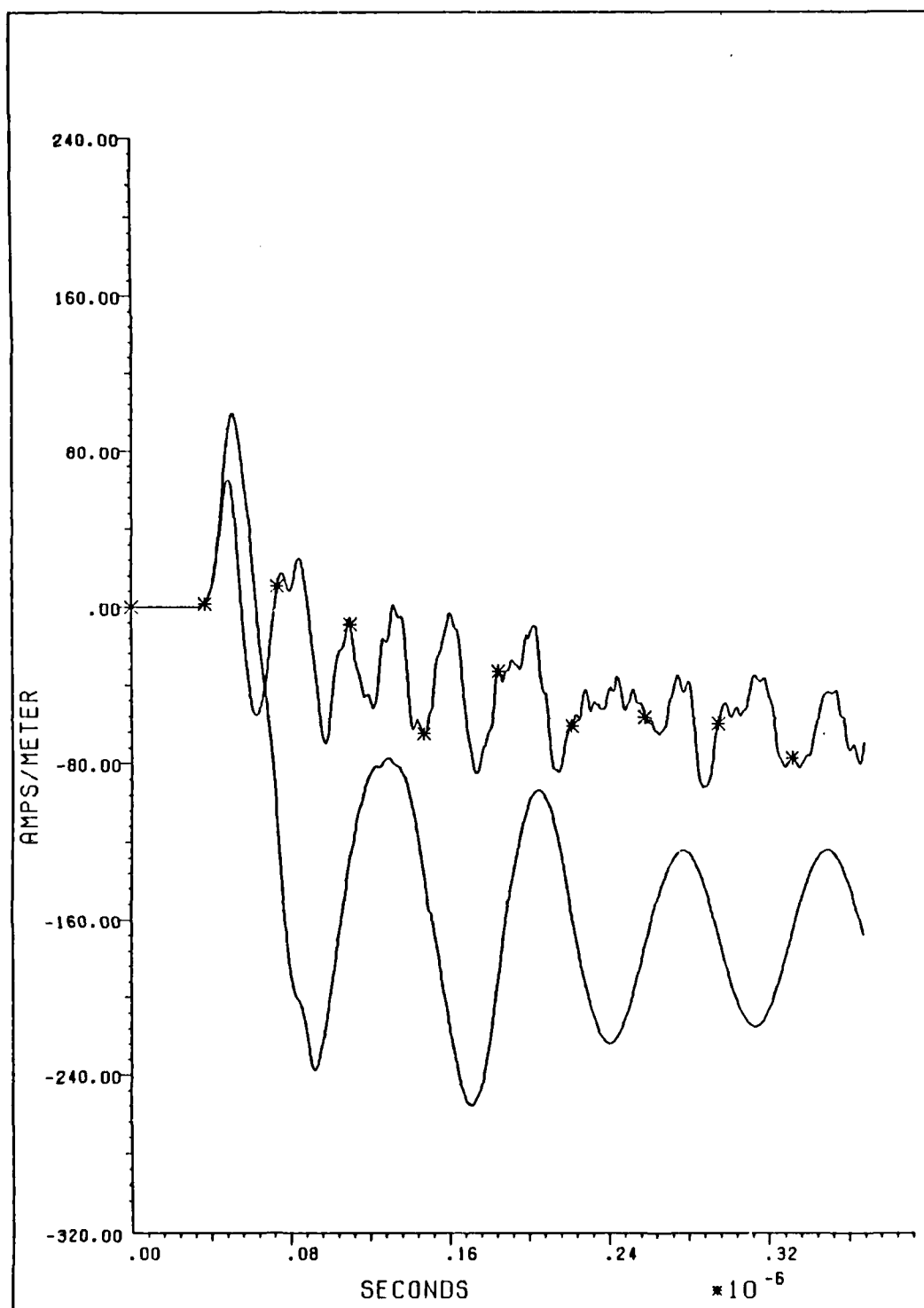
Figure 17. Sensor One, H-field, Right Wing

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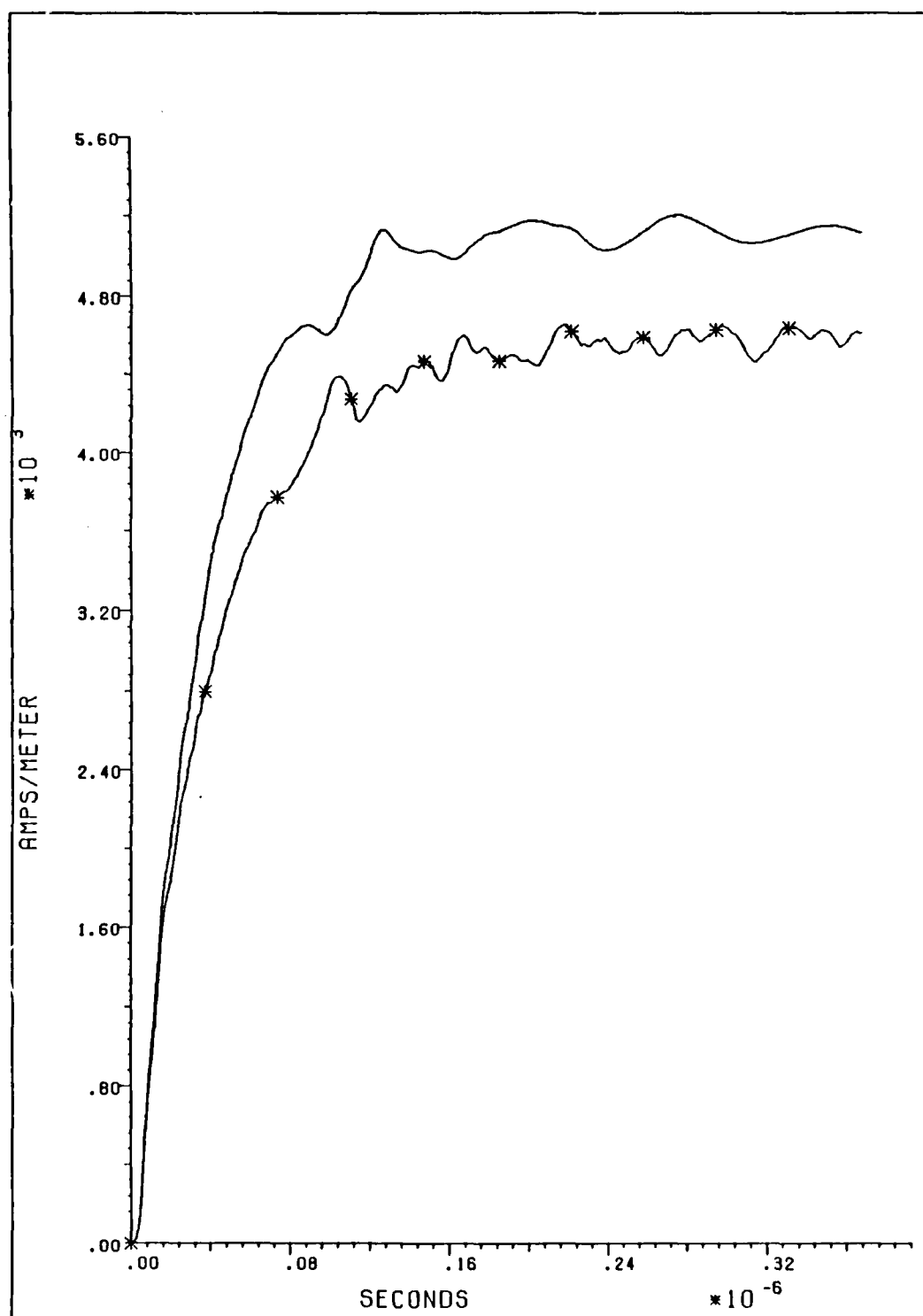
Figure 18. Sensor Two, H-field, Nose

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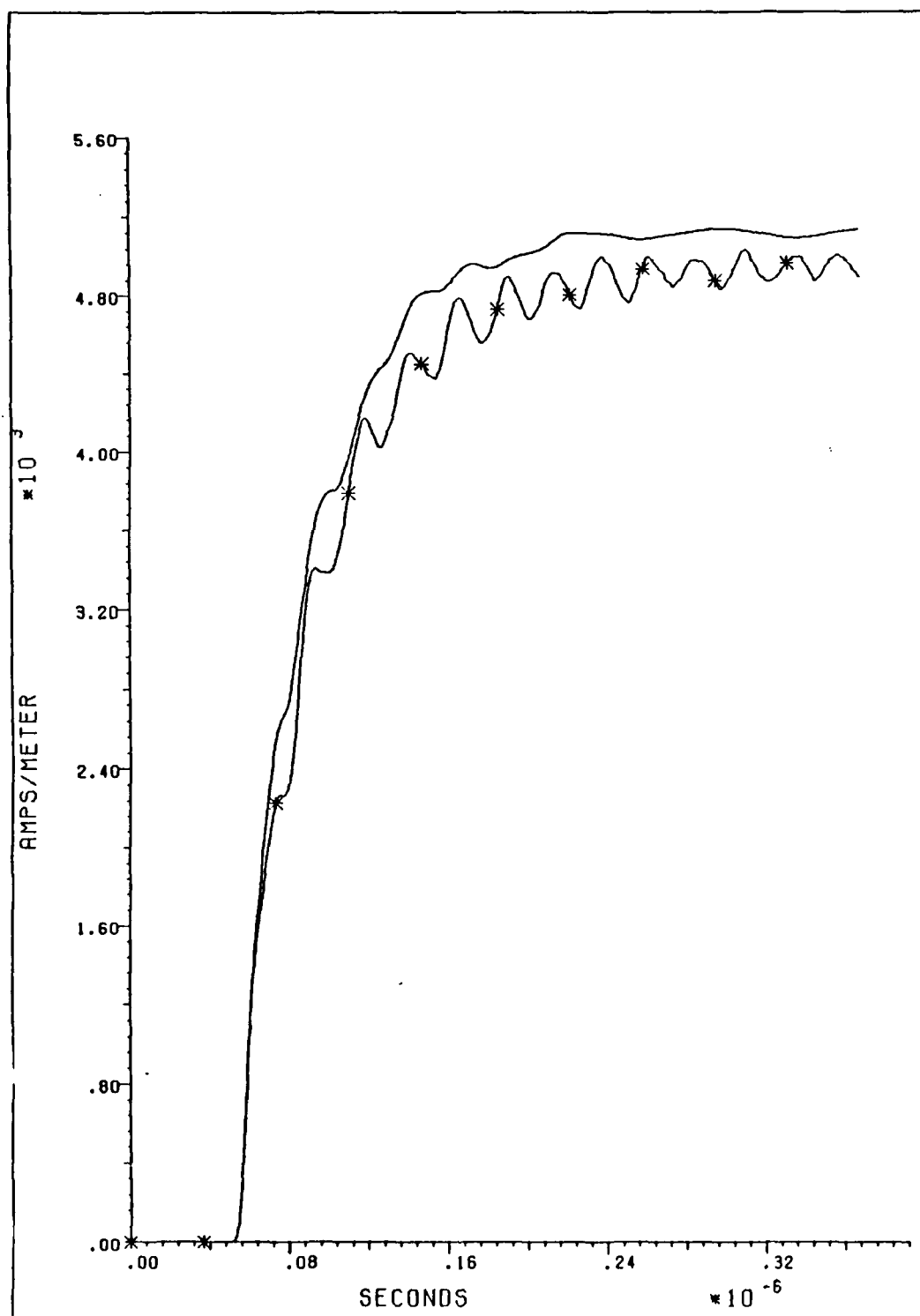
Figure 19.   Sensor Three, H-field, Engine Burner Can

60
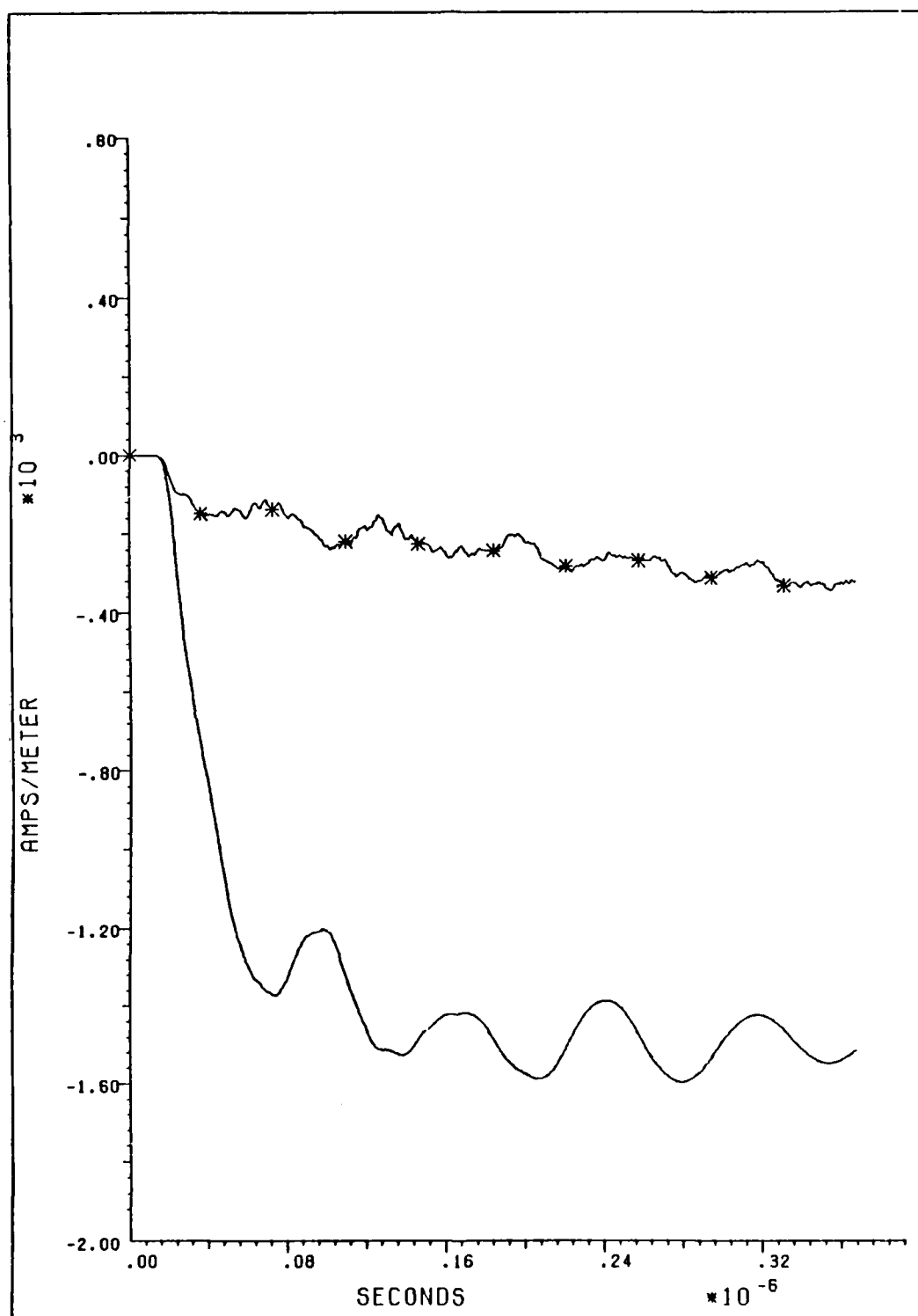
Figure 20. Sensor Four, H-field, Forward Fuselage Bottom

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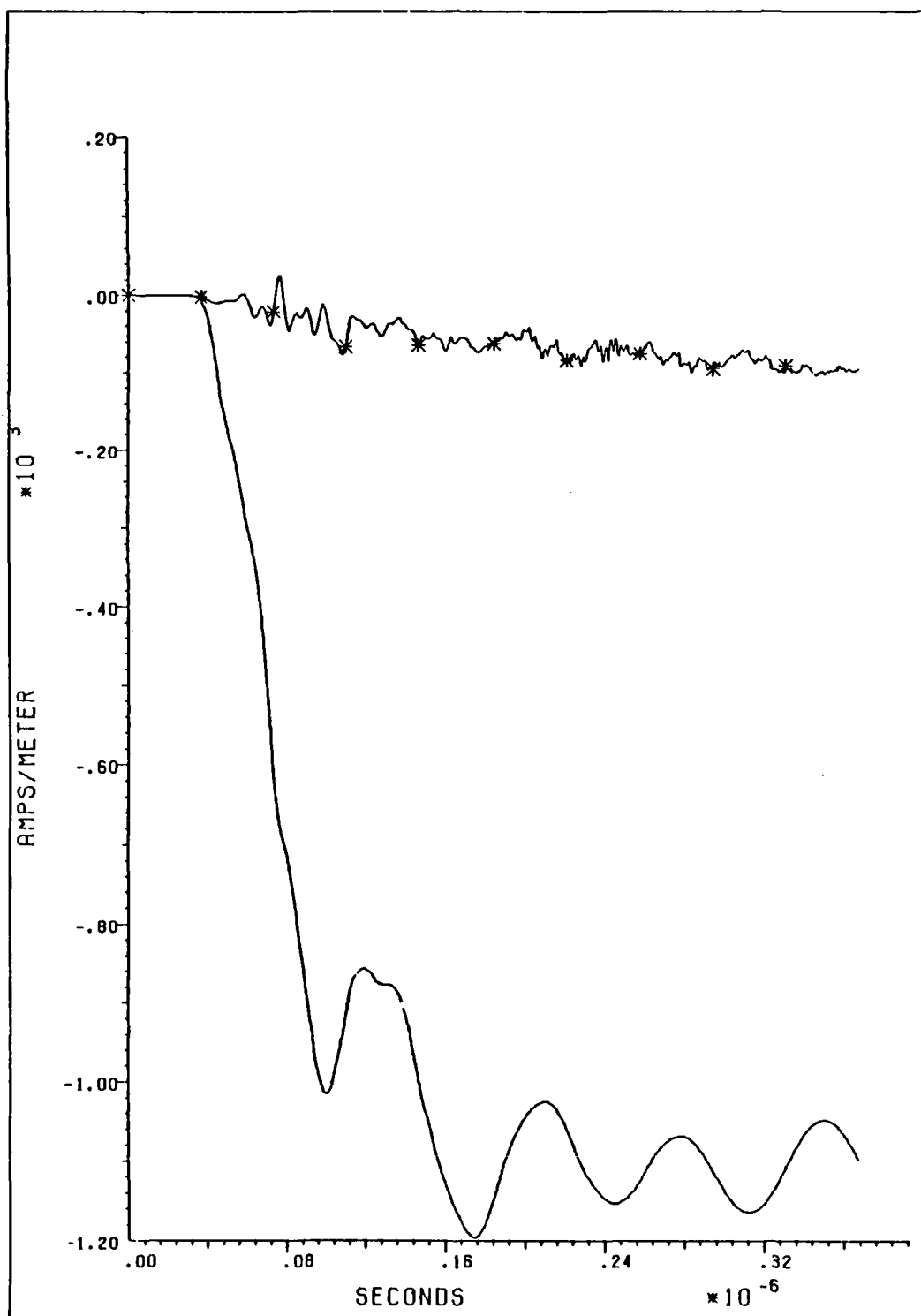
Figure 21. Sensor Five, H-field, Rear Fuselage Bottom
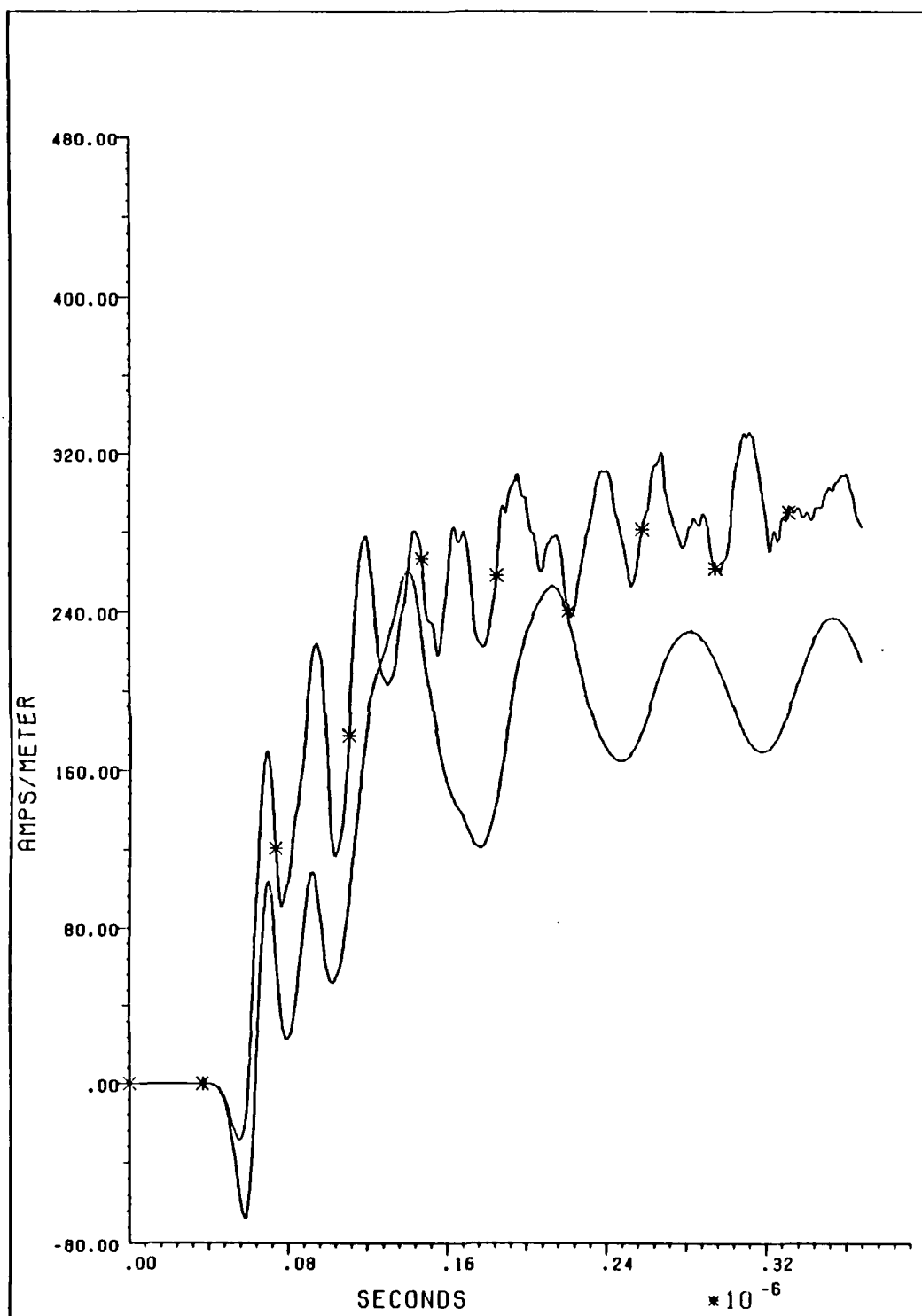
Figure 22. Sensor Six, H-field, Vertical Stabilizer

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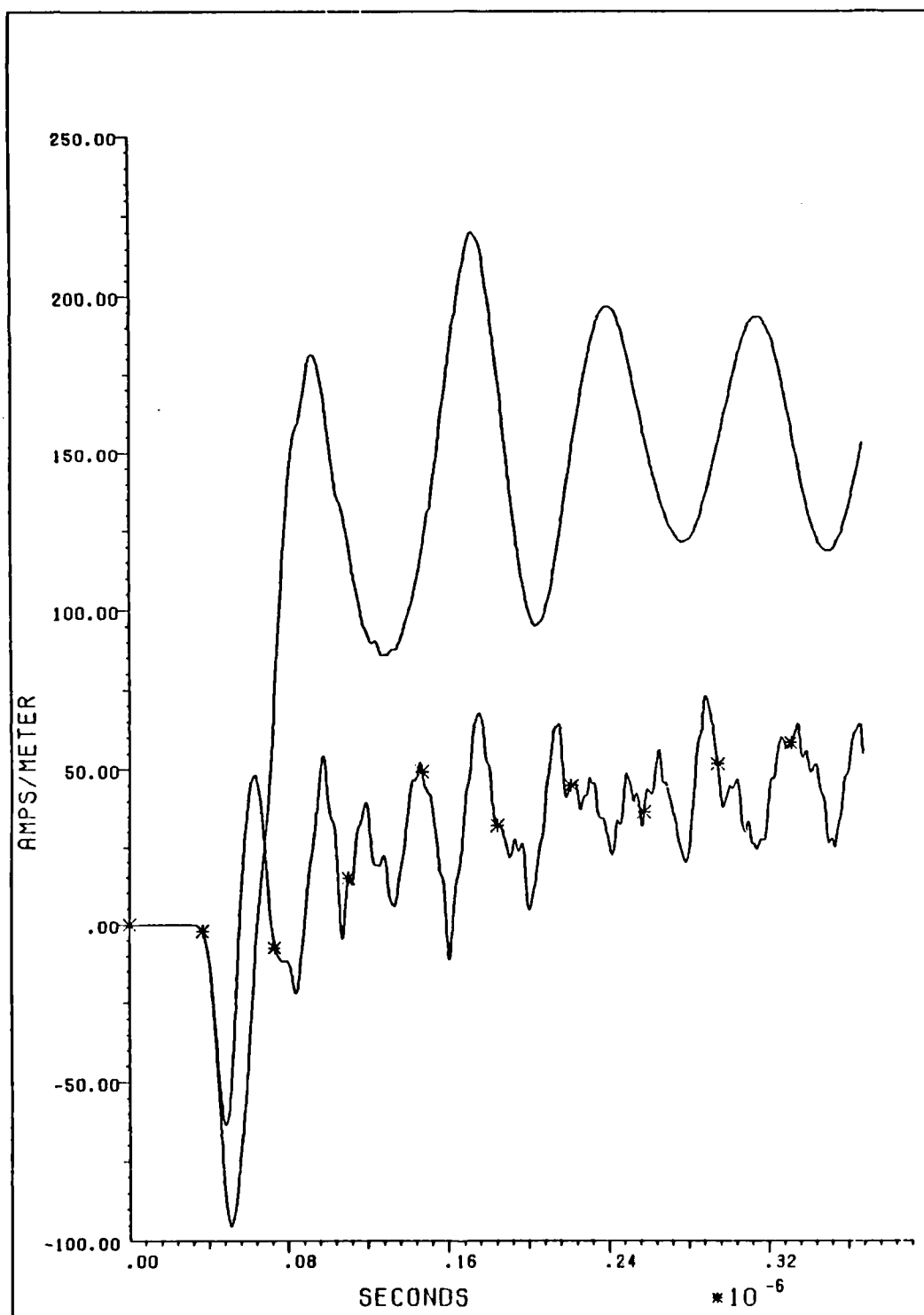
Figure 23.   Sensor Seven, H-field, Left Wing
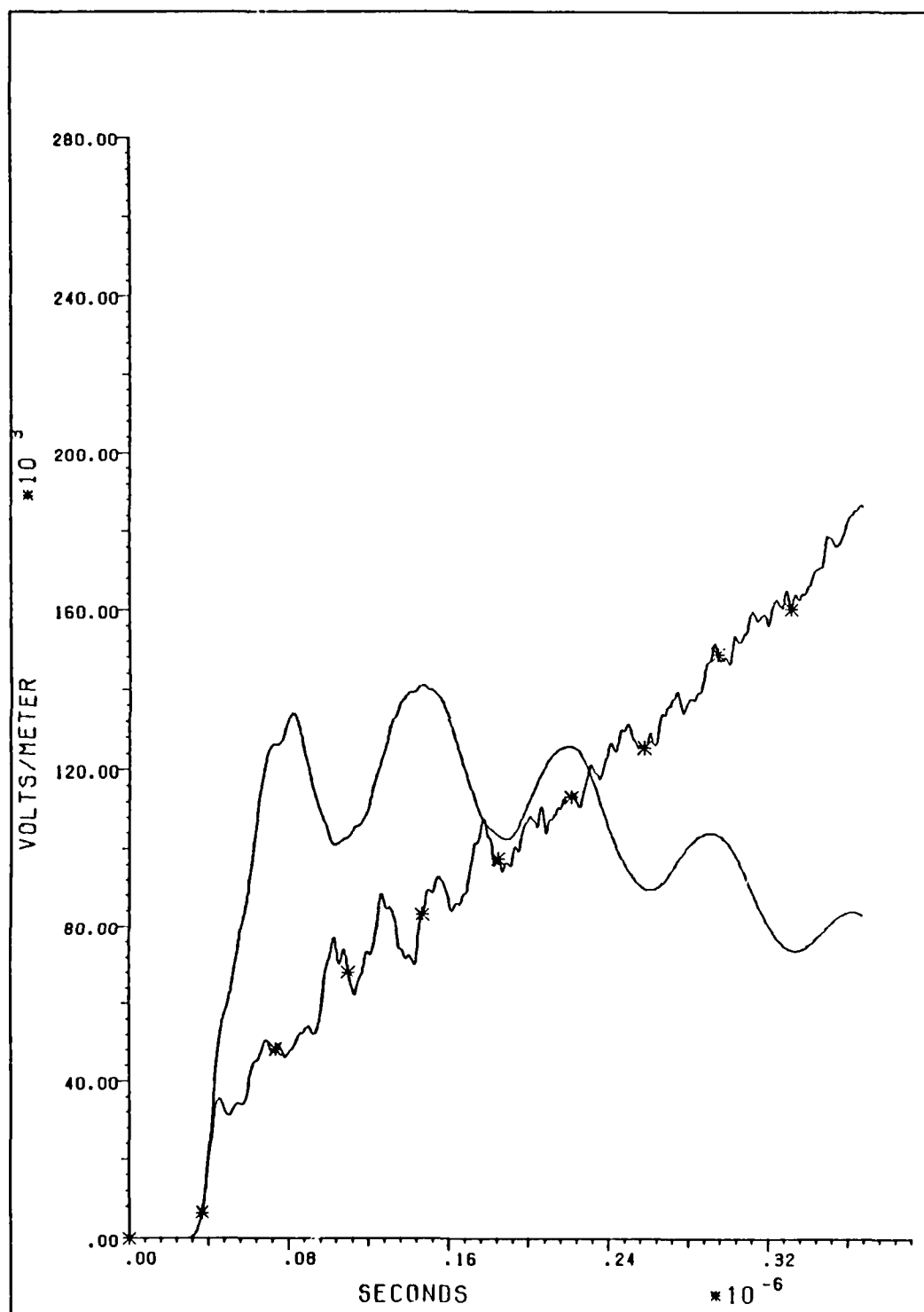
Figure 24.   Sensor Eight, E-field, Right Wing

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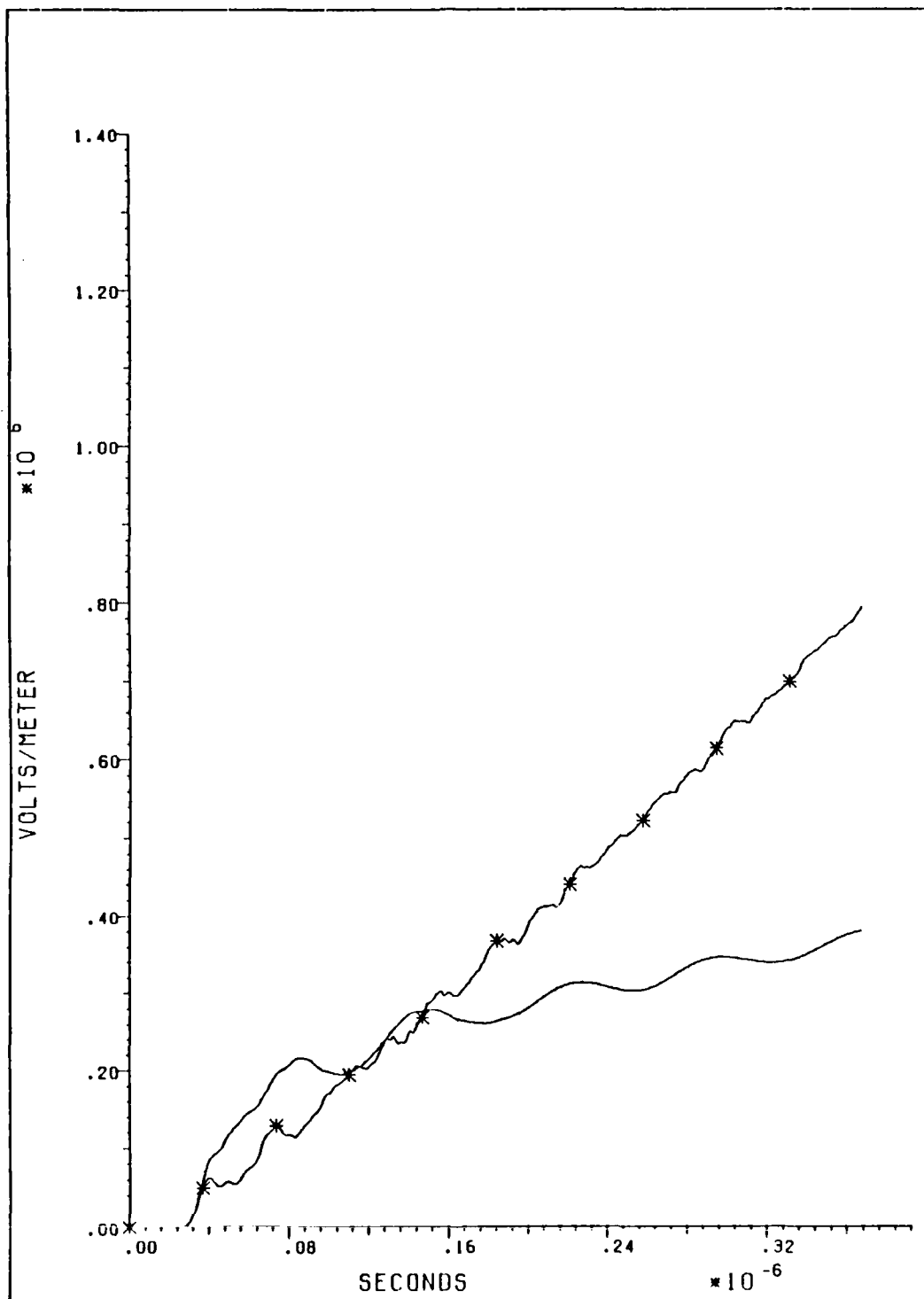
Figure 25. Sensor Nine, E-field, Middle Fuselage Top
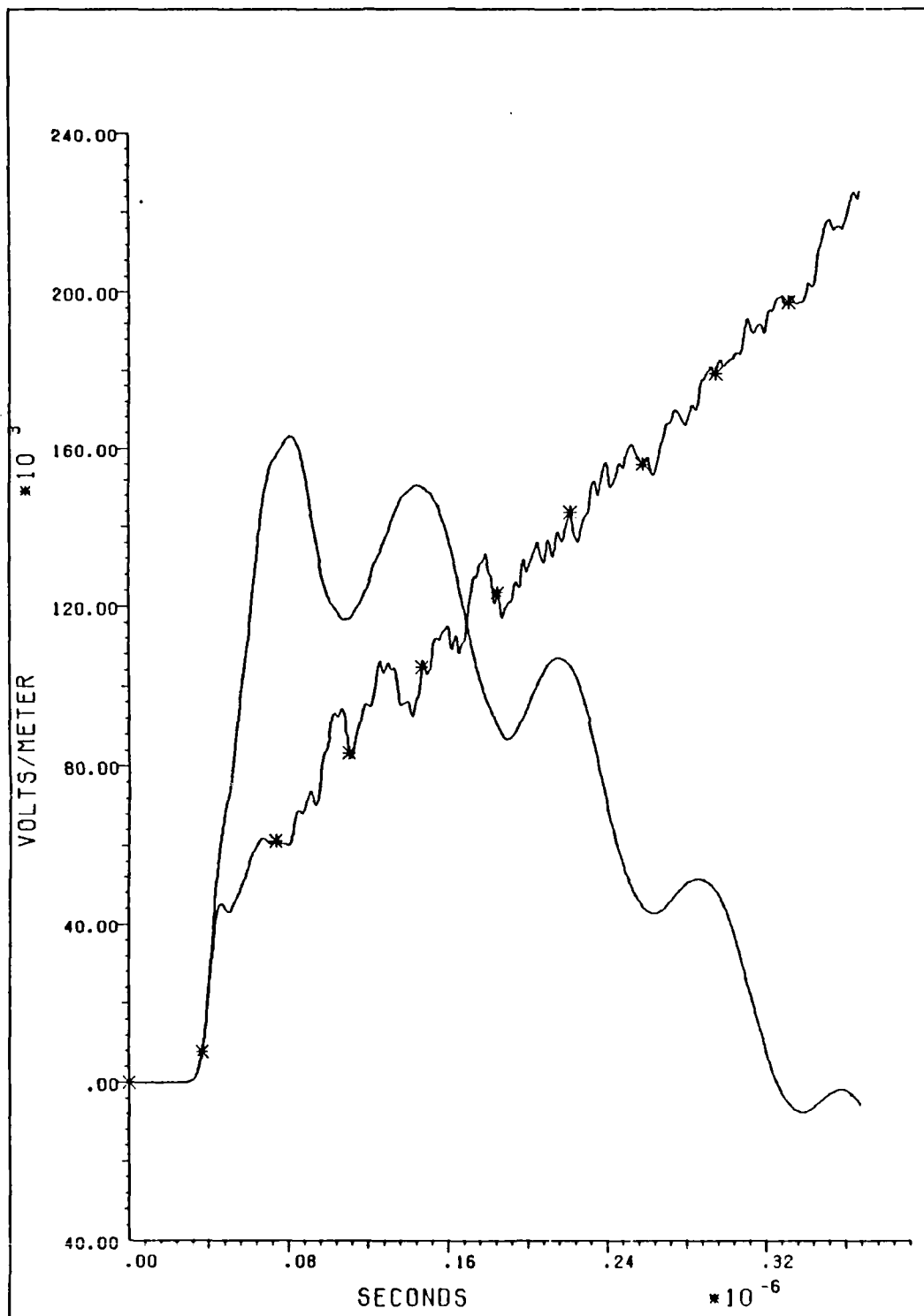
Figure 26.   Sensor Ten, E-field, Left Wing

Waveform Appearance

The general appearance of the responses from the different boundary conditions was dramatic. The amplitude oscillation frequency of the radiation boundary condition response was less distinct than that of the absorption boundary condition. As Figure 17 thru Figure 26 display, the radiation condition gave a much smoother response. The overall response for the entire two microseconds of each of the computer runs was consistent. In each and every graph of the response, the radiation boundary condition curve was smoother and settled to a steady state response much quicker than that of the absorption boundary condition.

Note also that the amplitude, in general, of the radiation boundary curves are higher than those of the absorption boundary condition. This lower absorption amplitude was due in part to the source itself being absorbed. That is, the source actually goes through a couple of element blocks which have a finite conductivity. However, a small portion of the amplitude differences could be due to constructive and destructive interference of the reflected and surface waves.

The absorption boundary condition's H-field response of Figure 17 has an average period of 3.6 nanoseconds, which corresponds to a wavelength of 1.08 meters. The radiation boundary condition's H-field response for the same time span is different (Figure 17). It has a average period of 7.2 nanoseconds, which corresponds to a wavelength of 2.16 meters. Using the aircraft's length as the predominant resonance structure, the wavelength of the response calculated for radiation boundary conditions was a quarter wavelength multiple of the aircraft's length. The absorption boundary condition did not have this same relationship, as its multiple was in thirds of the aircraft's length. This is only a general conclusion. Time did not permit taking the major surface dimensions of each sensor's local area, and correlating the calculated field response's frequency to the major local surface dimensions. But, the result is as expected; that is, the major geometrical object's characteristic wavelength will dominate. More time would have permitted looking at the problem space's dominant cavity frequency, and its contribution to the response curve's shape.

Program Considerations

Implementing the radiation boundary conditions has many effects. One positive effect was just discussed, that of smoothing the response waveform. Other effects, such as increased storage and run time, are not desirable. The amount of storage for running the program of Appendix A with its absorption boundary condition is doubled when the radiation boundary condition is implemented. An additional 363 lines of code were added to the program, to implement the radiation boundary condition. The worst effect was the CPU time per 100 nanoseconds of program time increased by 25% for the radiation boundary condition over the absorption boundary condition. Table 2 contains some details from the CDC Cyber 845 after the first 100 nanoseconds of data was calculated. No claim is made that any code optimization for run time, speed or memory utilization was attempted. However these times are comparable to those given in Eriksen's report (13:50). This is a first attempt at a comparison on the same code with only the boundary condition changed. The similarity of the plots at each sensor alone, support the validity of the program as modified with radiation boundary conditions.

TABLE 2. CDC Cyber 845 Computer Run Data

	Absorption Boundary Condition	Radiation Boundary Condition	Percent Increase
Time elapsed within program	100 ns	100 ns	-
SRU's CDC 845	8388.6	11534.3	37.5
CPU seconds execution time	3471.4	4341.2	25.1
Number cycles through program	272	272	-
CPU cost @ $320/hour	$308.57	$385.88	25.1
Cost per cycle (0.1833 ns)	$1.13	$1.42	25.1

Conclusion

The smoother response curves of the radiation boundary condition are quite clear. Assuming this smoothing is due to ridding the solution of unwanted resonances by changing the boundary conditions, a more accurate result has been accomplished. But, as with all things, more study needs to be done before real confidence can be placed in this computer solution. Checks were run on both of the computer programs to verify them. Techniques, such as running the codes without sources, or without an object in the problem space, were performed. The results of the checks of the

program proved that it worked properly in those aspects. But more experimentation needs to be performed. On the surface, the radiation boundary conditions give response curves of the same general shape as found in lightning strike characterization papers. This comparison is made, in general, with other calculation methods of response curve generation. A lot of questions yet to be answered have to do with whether or not the increased cost of this program is justified. Can the analysis be accomplished, with the results of the absorption boundary conditions, to the desired accuracy? Which degree of accuracy is needed? What is the decision point for using one boundary condition over the other?

In comparing the response curves side-by-side, it is noted that the general wave patterns for each sensor are the same. Therefore, implementing the radiation boundary condition did not alter the basic wave pattern. And the radiation boundary condition did smooth the waveforms. This tends to back up the premise that the spurious reflections caused by the absorption boundary condition's changes in conductivity, are seemingly removed by the radiation boundary condition. The objective of ridding the output of spurious reflections seems to have been accomplished.

7. Summary and Recommendations

The major objectives of this study have been successfully completed. The code for modeling an F-16 into the Rymes' 3DFD computer code was written and implemented successfully. The 3DFD computer code was run with absorption boundary conditions for two microseconds of response time. The 3DFD code was then rewritten to incorporate the radiation boundary conditions, and run with the radiation boundary conditions for two microseconds of response time. During each complete run, ten points on the surface of the simulated aircraft were sampled. These samples are in the form of magnetic field responses and electric field responses.

The responses for each sample point were compared for the different boundary conditions. The radiation boundary condition produced a much smoother response, apparently accomplishing the task set forth by the sponsor, AFWAL/FIESL. That is, the radiation boundary conditions removed many of the unwanted variations in the amplitude. The major drawbacks of implementing the radiation boundary conditions over the absorption boundary conditions were discussed. The 25% increase in the cost of running the radiation boundary condition program was a major disadvantage. However, the overall results verified that

the radiation boundary conditions do remove unwanted problem space reflections. The sponsor (AFWAL/FIESL) was very pleased with the results.

Future projects to parallel this effort could be numerous. Comparisons should be made of 3DFD output data with measured, actual inflight lightning strikes. Another possibility, would be exploring in greater detail the result of this study for more subtle effects of the different boundary conditions that were not readily apparent. Or researchers could take on the very challenging task of optimizing the code for minimum run time and maximum efficiency in storage use. A detailed examination should be made to explain why the E-fields of sensors 8 and 10, seem to have opposite polarities for the different boundary conditions. An interesting technique would be to use the aircraft symmetry in such a manner that only half the problem need be solved, which, in theory, would reduce the expense by half. Researching combinations of boundary conditions would also be of great interest. One possibility would be to allow a small amount of absorption in the outermost cell, in combination with the radiation condition. Another possibility would be to create variations in the cell dimensions in a given direction, as opposed to adding extra grid cells (which cause cost increases or loss of details in the modeling of the object being studied).

Many studies have been performed in the area of Finite Difference Codes, as attested to by the many listings in the bibliography. However, few real comparisons of the varied techniques are available in any detail. Much can be accomplished with this code. The 3DFD is very flexible and allows cell-by-cell assignment of material properties. This flexibility makes this code an issue of possibly great interest in the study of composite aircraft materials in many electromagnetic pulse environments.

Future implementation on specialized parallel processing computers, and/or the CRAY super computer, would greatly reduce the major disadvantage of the 3DFD code, which is the CPU runtime. Of course, the increased cost of the use of these newer computers must be weighed against the benefits. The last suggestion that will be made in this thesis is that an interactive modeling system be developed for electromagnetic codes in general. Modeling an aircraft is a very time-consuming task. Cooperation with the aeronautical engineers and their detailed drawing capabilities would open new frontiers for the electromagnetic community. The ability to take the aeronautical engineer's detailed structural drawing and converting them into electromagnetic models by software, would be a great stride forward for any electromagnetic computer code utilization.

Appendix A

Updated Modified Rymes' Code

This appendix contains the Modified Rymes' Code, with absorption boundary conditions, written by Hebert (16). The code listing is complete as implemented and runs on a CDC Cyber 845. Improvements are included which correct minor errors in the code mechanics, and an improved source is also implemented. The code compiles on the Cyber 845 using FTN5, and runs with no problem when suppressing ANSI errors. The compile time is approximately 2.603 CPU seconds. The run time is 3,472 CPU seconds for 100 nanoseconds of sample time elapsed. The aircraft modeled in this code is an F-16 'Fighting Falcon'. This code will run as listed only for the first 150 nanoseconds. For continued runs, modifications must be made as annotated in the program. Additionally 'TAPE1' must be saved from the previous run.

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```
        PROGRAM ABC (OUTF15,TAPE4=OUTF15,TAPE2)
C
C       THE MODIFIED RYMES 3-D CODE F16
C
        COMMON /SET1/ NMAX,EPST,SIG0,C,TMUO,DELT
        COMMON /SET2/ ICAN,ICM1,ICP1,JCAN,JCM1,JCP1,KCAN,KCM1,KCP1
        COMMON /SET3/ DELX,DELY,DELZ
        COMMON /TIME/ TEN,THN
        COMMON /ARRAYS/ A1(27,27),B1(39),A2(27,27),B2(39),A3(27,27),
       +B3(39),A4(27,27),B4(39),A5(27,27),B5(39),A6(27,27),B6(39),
       +A7(27,27),B7(39),A8(27,27),B8(39),A9(27,27),B9(39),
       +A10(27,27),B10(39),A11(27,27),B11(39)
        DIMENSION INDEX(190)
        CALL OPENMS(2,INDEX,190,0)
C
C       READ INPUT DATA
C
        CALL SETUP
C
C       ZERO THE FIELDS INITIALLY.
C       PROGRAM USES A MASTER STORAGE FILE TO STORE FIELDS AND CONDUCTIVITY
C       OF EACH LATTICE POINT. INDEX K GOES FROM 1 TO 27.
C       EX   K
C       EY   K+27
C       EZ   K+54(27*2)
C       HX   K+81(27*3)
C       HY   K+108(27*4)
C       HZ   K+135(27*5)
C       SIG  K+162(27*6)
C
C**************************************************
C************DELETE FROM HERE TO STOP DELETE********
C          TO REMOVE THE ZEROING OF TAPE1
C          FOR CONTINUED RUNS BEYOND THE
C          INITIAL TMAX STOPPING TIME
        DO 100 I=1,27
        DO 100 J=1,27
100     A1(I,J)=0.0
        DO 200 K=1,189
200     CALL WRITMS(2,A1(1,1),768,K,0)
C
C************STOP DELETE GO THE THN/TEN************
C*****************************************************
C       PRESET THE CONDUCTIVITY ARRAY
C
        CALL SIGSET
C
C       TIME STEP LOOP
C
        DO 1000 N=1,NMAX
        CALL APERT
C
```

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```
C     COMPUTE TIME CONSTANTS
C
C****************************************************
C************FOR CONTINUED RUNS BEYOND TMAX**********
C          ADD THE STOPPING TIME FROM PREVIOUS
C          RUNS TO THN AND TEN PLUS 1/2 OF DELTA T
C
C          ...
C        EXAMPLE
C
C       AFTER FIRST RUN
C
C       THN=DELT*(FLOAT(N)-1.0)+1.50183E-7
C       TEN=DELT*(FLOAT(N)-.5)+1.50183E-7
C****************************************************
      THN=DELT*(FLOAT(N)-1.0)
      TEN=DELT*(FLOAT(N)-.5)
C
C     ADVANCE THE H-FIELDS BY Z-PLANES
C
      CALL HADV
C
C     ADVANCE THE E-FIELDS BY Z-PLANES
C
      CALL EADV
1000  CONTINUE
C
C     END OF TIME LOOP
C
      CALL CLOSMS(2)
      STOP
      END
      SUBROUTINE SETUP
C
C     CODE USES A UNIFORM GRID.
C
      COMMON /SET1/ NMAX,EPST,SIG0,C,TMUO,DELT
      COMMON /SET2/ ICAN,ICM1,ICP1,JCAN,JCM1,JCP1,KCAN,KCM1,KCP1
      COMMON /SET3/DELX,DELY,DELZ
C
C     INPUT DATA PROVIDED BY USER.
C
      DATA C,EPSO,EPSR,XMUO,SIG0/3.0E8,8.8542E-12,1.0,1.2566E-6,1.E-4/
      DATA ICP1,JCP1,KCP1/27,27,27/
      DATA DELX,DELY,DELZ/.69,.22,.45/
      DATA TMAX/1.5E-7/
C
      ICAN=ICP1-1
      ICM1=ICAN-1
      JCAN=JCP1-1
      JCM1=JCAN-1
      KCAN=KCP1-1
```

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```
          KCM1=KCAN-1
C
C     VERIFY THAT ICP1,JCP1,KCP1 ARE ODD.
C
      IF(ICAN.EQ.2*(ICAN/2).AND.JCAN.EQ.2*(JCAN/2).AND.
     +KCAN.EQ.2*(KCAN/2))GO TO 1
      PRINT *,' THE NUMBER OF GRID POINTS MUST BE ODD '
      STOP
1     CONTINUE
C
C     DELT IS THE TIME INCREMENT (IT SATISFIES COURANT CONDITION).
C     NMAX IS THE TOTAL NUMBER OF TIME INCREMENTS FIELDS WOULD BE ADVANCED.
C
      DELT=AMIN1(DELX,DELY,DELZ)/(2.*C)
      NMAX=TMAX/DELT
      EPST=EPSO*EPSR/DELT
      TMUO=DELT/XMUO
      RETURN
      END
      SUBROUTINE SIGSET
C
C     SIG(I,J) AT K1=K+162 IS THE CONDUCTIVITY AT THE POINT (X(I),Y(J),Z(K)).
C     X(I)=(I-.5)*DELX, Y(J)=(J-.5)*DELY, Z(K)=(K-.5)*DELZ
C
      COMMON /ARRAYS/ SIG(27,27),B1(39)
      COMMON /SET1/ NMAX,EPCT,SIGO,C,TMUO,DELT
      COMMON /SET2/ ICAN,ICM1,ICP1,JCAN,JCM1,JCP1,KCAN,KCM1,KCP1
C
C     PRESET THE CONDUCTIVITY TO 1E-4 EVERYWHERE IN SPACE.
C
      DO 10 I=1,ICAN
      DO 10 J=1,JCAN
10    SIG(I,J)=SIGO
C
C     NOW WRITE THE SIG ARRAY TO MASS STORAGE
C
      DO 20 K=1,KCAN
      K1=K+162
20    CALL WRITMS(2,SIG(1,1),768,K1,1)
C
C     THEN ESTABLISH FREE SPACE CONDITIONS
C
      ICM2=ICAN-2
      JCM2=JCAN-2
      KCM2=KCAN-2
      DO 30 I=3,ICM2
      DO 30 J=3,JCM2
30    SIG(I,J)=0.0
C
C     NOW OVERWRITE THIS PORTION OF THE SIG ARRAY
C
      DO 40 K=3,KCM2
```

```
        K1=K+162
40      CALL WRITMS(2,SIG(1,1),768,K1,1)
        RETURN
        END
        SUBROUTINE EADV
C
C       THIS SUBROUTINE ADVANCES THE E-FIELDS  TWO Z-PLANES AT A TIME.
C       RECORDS OF H-FIELDS FOR TWO SUCCESIVE Z-PLANES MUST BE KEPT IN
C       ORDER TO TAKE DERIVATIVES IN THE Z-DIRECTION.
C       RECORDS OF SIG FOR TWO SUCCESIVE Z-PLANES MUST BE KEPT IN ORDER TO TAKE
C       AVERAGES IN THE Z-DIRECTION.
C
        COMMON /SET!/NMAX,EPST,SIG0,C,TMU0,DELT
        COMMON /SET2/ ICAN,ICM1,ICP1,JCAN,JCM1,JCP1,KCAN,KCM1,KCP1
        COMMON /SET3/ DELX,DELY,DELZ
        COMMON /TIME/ TEN,THN
        COMMON /ARRAYS/ EX(27,27),B1(39),EY(27,27),B2(39),EZ(27,27),
       +B#(39),HXA(27,27),B4(39),HXB(27,27),B5(39),HYA(27,27),B6(39),
       +HYB(27,27),B7(39),HZA(27,27),B8(39),HZB(27,27),B9(39),
       +SIGA(27,27),B10(39),SIGB(27,27),B11(39)
C
C       ADVANCE E-FIELDS BY Z-PLANES
C       READ IN FIRST H-PLANES
C
        CALL READMS(2,HXA(1,1),768,82)
        CALL READMS(2,HYA(1,1),768,109)
C
C       DO FOR ALL Z-PLANES
C
        MN8=8
        MN9=9
        MN10=10
        DO 1000 KLOOP=1,KCAN,2
        K=KLOOP
        KP1=K+1
        K2=K+27
        K3=K+54
        K4=K+82
        K5=K+109
        K6=K+135
        K7=K+162
C
C       READ IN SECOND H-PLANES AND OLD E-FIELDS
C
        CALL READMS(2,EX(1,1),768,K)
        CALL READMS(2,EY(1,1),768,K2)
        CALL READMS(2,EZ(1,1),768,K3)
        CALL READMS(2,HXB(1,1),768,K4)
        CALL READMS(2,HYB(1,1),768,K5)
        CALL READMS(2,HZA(1,1),768,K6)
        CALL READMS(2,SIGA(1,1),768,K7)
C
```

```
      DO 200 J=1,JCAN
      JP1=J+1
      DO 200 I=2,ICAN
C
C     SIG(X0,Y,Z)=.5*(SIG(X-DELX,Y,Z)+SIG(X,Y,Z))
C     SIG(X,Y0,Z)=.5*(SIG(X,Y-DELY,Z)+SIG(X,Y,Z))
C     SIG(X,Y,Z0)=.5*(SIG(X,Y,Z-DELZ)+SIG(X,Y,Z))
C
      SIG2=.25*(SIGA(I,J)+SIGA(I-1,J))
      A=EPST-SIG2
      B=1./(EPST+SIG2)
      EX(I,J)=(A*EX(I,J)+(HZA(I,JP1)-HZA(I,J))/DELY -
     +(HYB(I,J)-HYA(I,J))/DELZ)*B
200   CONTINUE
      DO 300 I=1,ICAN
      IP1=I+1
      DO 300 J=2,JCAN
      SIG2=.25*(SIGA(I,J-1)+SIGA(I,J))
      A=EPST-SIG2
      B=1./(EPST+SIG2)
      EY(I,J)=(A*EY(I,J)+(HXB(I,J)-HXA(I,J))/DELZ -
     +(HZA(IP1,J)-HZA(I,J))/DELX)*B
300   CONTINUE
C
C     WRITE NEW EX,EY PLANES TO MASS STORAGE
C
      CALL WRITMS(2,EX(1,1),768,K,1)
      CALL WRITMS(2,EY(1,1),768,K2,1)
      IF (K.EQ.1)GO TO 450
      DO 400 I=1,ICAN
      IP1=I+1
      DO 400 J=1,JCAN
      JP1=J+1
      SIG2=.25*(SIGA(I,J)+SIGB(I,J))
      A=EPST-SIG2
      B=1./(EPST+SIG2)
      EZ(I,J)=(A*EZ(I,J)+(HYA(IP1,J)-HYA(I,J))/DELX-
     +(HXA(I,JP1)-HXA(I,J))/DELY)*B
400   CONTINUE
C
C     WRITE NEW EZ PLANE TO MASS STORAGE
C
      CALL WRITMS(2,EZ(1,1),768,K3,1)
C
C     SAMPLE POINTS OF INTEREST(ODD K PLANES)
C
111      FORMAT (I4,2(1X,1P1E11.4))
112      FORMAT (I4,2(1X,1P1E11.4),2(/))
C
L
450   CONTINUE
      K=KP1
```

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```
      KP1=K+1
      K2=K2+1
      K3=K3+1
      K4=K4+1
      K5=K5+1
      K6=K6+1
      K7=K7+1
C
C     READ IN SECOND OLD E-PLANES AND NEXT H-PLANES OFER A PLANE
C
      CALL READMS(2,EX(1,1),768,K)
      CALL READMS(2,EY(1,1),768,K2)
      CALL READMS(2,EZ(!,1),768,K3)
      CALL READMS(2,HXA(1,1),768,K4)
      CALL READMS(2,HYA(1,1),768,K5)
      CALL READMS(2,HZB(1,1),768,K6)
      CALL READMS(",SIGB(1,1),768,K7)
      DO 600 J=1,JCAN
      JP1=J+1
      DO 600 I=2,ICAN
      SIG2=.25*(SIGB(I,J)+SIGB(I-1,J))
      A=EPST-SIG2
      B=1./(EPST+SIG2)
      EX(I,J)=(A*EX(I,J)+(HJB(I,JP1)-HZB(I,J))/DELY -
     +(HYA(I,J)-HYB(I,J))/DELZ)*B
600   CONTINUE
      DO 700 I=1,ICAN
      IP1=I+1
      DO 700 J=2,JCAN
      SIG2=.25*(SIGB(I,J-1)+SIGB(I,J))
      A=EPST-SIG2
      B=1./(EPST+SIG2)
      EY(I,J)=(A*EY(I,J)+(HXA(I,J)-HXB(I,J))/DELZ -
     +(HZB(IP1,J)-HZB(I,J))/DELX)*B
700   CONTINUE
      DO 800 I=1,ICAN
      IP1=I+1
      DO 800 J=1,JCAN
      JP1=J+1
      SIG2=.25*(SIGB(I,J)+SIGA(I,J))
      A=EPST-SIG2
      B=1./(EPST+SIG2)
      EZ(I,J)=(A*EZ(I,J)+(HYB(IP1,J)-HYB(I,J))/DELX -
     +(HXB(I,JP1)-HXB(I,J))/DELY)*B
800   CONTINUE
C
C     WRITE NEW EX,EY,EZ PLANES TO MASS STORAGE
C
      CALL WRITMS(2,EX(1,1),768,K,1)
      CALL WRITMS(2,EY(1,1),768,K2,1)
      CALL WRITMS(2,EZ(1,1),768,K3,1)
C
```

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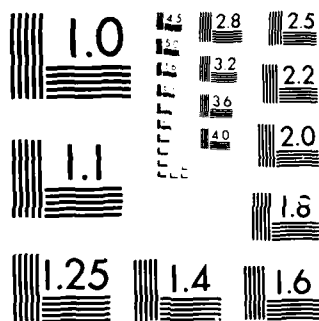
END

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MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS 1963-A

```
C     SAMPLE POINTS OF INTEREST (EVEN K PLANES)
C
       IF (K.EQ.10) WRITE (4,111) MN8,TEN,EY(17,11)
       IF (K.EQ.18) WRITE (4,112) MN10,TEN,EY(17,11)
C
      IF (K.EQ.14)  THEN
        WRITE (4,111) MN9,TEN,EY(15,13)
       ELSE
       END IF
C
1000  CONTINUE
C
C     ZERO THE ELECTRIC FIELD WITHIN THE METAL COMPONENTS OF AIRCRAFT.
C
      CALL AIRPLN
      RETURN
      END
      SUBROUTINE HADV
C
C     THIS SUBROUTINE ADVANCES THE H-FIELDS TWO Z-PLANES AT A TIME.
C     RECORDS OF E-FIELDS FOR TWO SUCCESIVE PLANES MUST BE KEPT IN ORDER TO TAKE
C     DERIVATIVES IN THE Z-DIRECTION.
C
      COMMON /SET1/ NMAX,EPST,SIGO,C,TMUO,DELT
      COMMON /SET2/ ICAN,ICM1,ICP1,JCAN,JCM1,JCP1,KCAN,KCM1,KCP1
      COMMON /SET3/ DELX,DELY,DELZ
      COMMON /TIME/ TEN,THN
      COMMON /ARRAYS/ EXA(27,27),B1(3)),EXB(27,27),B2(39),
     +EYA(27,27),B3(39),EYB(27,27),B4(39),EZA(27,27),B5(39),
     +EZB(27,27),B6(39),HX(27,27),B7(39),HY(27,27),B8(39),
     +HZ(27,27),B9(39)
C
C     DO FOR ALL Z-PLANES
       MN1=1
       MN2=2
       MN3=3
       MN4=4
      MN5=5
      MN6=6
      MN7=7
C
      DO 900 KLOOP=1,KCAN,2
      K=KLOOP
      KM1=K-1
      K2=K+27
      K3=K+54
      K4=K+81
      K5=K+108
      K6=K+135
      CALL READMS(2,EXB(1,1),768,K)
      CALL READMS(2,EYB(1,1),768,K2)
      CALL READMS(2,HZ(1,1),768,K6)
```

```
      IF (K.EQ.1)GO TO 350
      CALL READMS(2,EZB(1,1),768,K3)
      CALL READMS(2,HX(1,1),768,K4)
      CALL READMS(2,HY(1,1),768,K5)
      DO 200 J=2,JCAN
      DO 200 I=1,ICAN
      HX(I,J)=HX(I,J)+TMUO*((EYB(I,J)-EYA(I,J))/DELZ -
     +(EZB(I,J)-EZB(I,J-1))/DELY)
200   CONTINUE
      DO 300 I=1,ICM1
      IP1=I+1
      DO 300 J=1,JCAN
      HY(IP1,J)=HY(IP1,J)+TMUO*((EZB(IP1,J)-EZB(I,J))/DELX -
     +(EXB(IP1,J)-EXA(IP1,J))/DELZ)
300   CONTINUE
C
C     APPROXIMATES H FIELDS IN PLANE PERPENDICULAR TO WIRE
C     BY H=I/2*PI*R.
C       SOURCE FUNCTION,ODD K REFERENCE PLANES, HY
C     CURRENT PULSE MOVING IN X DIRECTION ATTACHES TO THE NOSE OF THE AIRPLANE
C     AT (X,Y,Z)=(8,18,14), EXITS BY THE TAIL AT (X,Y,Z)=(22,18,14).
C     AT TIME T=0.0 PULSE IS LOCATED AT X0(8).
C
      IF(K.NE.15)GO TO 1
      DO 10 I=2,3
      TPULSE=THN-.69*(FLOAT(I)-3.)/C
      IF(TPULSE.LE.0.0)GO TO 10
C
        X=EXP(-3.5E04*TPULSE)-EXP(-2.625E7*TPULSE)
C
        HYS=7.07E3*X
      HY(I,9)=-HYS
10    CONTINUE
      DO 30 I=25,26
       TPULSE=THN-.69*(FLOAT(I)-3.0)/C
      IF(TPULSE.LE.0.0)GO TO 30
        X=EXP(-3.5E4*TPULSE)-EXP(-2.625E7*TPULSE)
        HYS=7.07E3*X
      HY(I,10)=-HYS
30    CONTINUE
1     CONTINUE
C
C     WRITE NEW HX,HY PLANES TO MASS STORAGE
C
      CALL WRITMS(2,HX(1,1),768,K4,1)
      CALL WRITMS(2,HY(1,1),768,K5,1)
350   CONTINUE
      DO 400 I=1,ICM1
      IP1=I+1
      DO 400 J=1,JCM1
      JP1=J+1
      HZ(IP1,JP1)=HZ(IP1,JP1)+TMUO*((EXB(IP1,JP1)-EXB(IP1,J))/DELY -
```

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```fortran
     +(EYB(IP1,JP1)-EYB(I,JP1))/DELX)
400   CONTINUE
C
C     WRITE NEW HZ PLANE TO MASS STORAGE
C
      CALL WRITMS(2,HZ(1,1),768,K6,1)
C
C     SAMPLE POINTS OF INTEREST (ODD K PLANES)
C
      IF (K.EQ.13) WRITE (4,111) MN2,THN,HZ(4,10)
      IF (K.EQ.13) WRITE (4,111) MN3,THN,HZ(24,11)
      IF (K.EQ.23) WRITE (4,111) MN7,THN,HX(18,10)
C
112   FORMAT (I4,2(1X,1P1E11.4),2(/))
111   FORMAT (I4,2(1X,1P1E11.4))
C
      K=K+1
      KM1=K-1
      K2=K2+1
      K3=K3+1
      K4=K4+1
      K5=K5+1
      K6=K6+1
C
C     READ IN NEXT PLANES OF E AND H
C
      CALL READMS(2,EXA(1,1),768,K)
      CALL READMS(2,EYA(1,1),768,K2)
      CALL READMS(2,EZA(1,1),768,K3)
      CALL READMS(2,HX(1,1),768,K4)
      CALL READMS(2,HY(1,1),768,K5)
      CALL READMS(2,HZ(1,1),768,K6)
      DO 600 J=1,JCM1
      JP1=J+1
      DO 600 I=1,ICAN
      HX(I,JP1)=HX(I,JP1)+TMUO*((EYA(I,JP1)-EYB(I,JP1))/DELZ -
     +(EZA(I,JP1)-EZA(I,J))/DELY)
600   CONTINUE
      DO 700 I=1,ICM1
      IP1=I+1
      DO 700 J=1,JCAN
      HY(IP1,J)=HY(IP1,J)+TMUO*((EZA(IP1,J)-EZA(I,J))/DELX -
     +(EXA(IP1,J)-EXB(IP1,J))/DELZ)
700   CONTINUE
C
C     SOURCE FUNCTION, EVEN K REFERENCE PLANES, HY
C
      IF (K.NE.14)GO TO 2
      DO 20 I=2,3
      TPULSE=THN-.69*(FLOAT(I)-3.)/C
      IF (TPULSE.LE.0.0)GO TO 20
      X=EXP(-3.5E4*TPULSE)-EXP(-2.625E7*TPULSE)
```

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```fortran
            HYS=7.07E3*X
            HY(I,9)=+HYS
20          CONTINUE
            DO 40 I=25,26
            TPULSE=THN-.69*(FLOAT(I)-3.)/C
            IF (TPULSE.LE.0.0)GO TO 40
               X=EXP(-3.5E4*TPULSE)-EXP(-2.625E7*TPULSE)
               HYS=7.07E3*X
            HY(I,10)=+HYS
40          CONTINUE
2           CONTINUE
         DO 800 I=1,ICM1
         IP1=I+1
         DO 800 J=1,JCM1
         JP1=J+1
         HZ(IP1,JP1)=HZ(IP1,JP1)+TMUO*((EXA(IP1,JP1)-EXA(IP1,J))/DELY -
        +(EYA(IP1,JP1)-EYA(I,JP1))/DELX)
800      CONTINUE
C
C
C
C        SOURCE FUNCTION, EVEN K REFERENCE PLANE, HZ
         IF(K.NE.14)GO TO 4
         DO 60 I=2,3
         TPULSE=THN-.69*(FLOAT(I)-3.)/C
         IF(TPULSE.LE.0.0)GO TO 60
            X=(EXP(-3.5E4*TPULSE)-EXP(-2.625E7*TPULSE))
            HZS=1.447E4*X
         HZ(I,9)=-HZS
         HZ(I,10)=+HZS
60          CONTINUE
         DO 80 I=25,26
         TPULSE=THN-.69*(FLOAT(I)-3.)/C
         IF(TPULSE.LE.0.0)GO TO 80
            X=(EXP(-3.5E4*TPULSE)-EXP(-2.625E7*TPULSE))
            HZS=1.447E4*X
         HZ(I,10)=-HZS
         HZ(I,11)=HZS
80          CONTINUE
4           CONTINUE
         CALL WRITMS(2,HX(1,1),768,K4,1)
         CALL WRITMS(2,HY(1,1),768,K5,1)
         CALL WRITMS(2,HZ(1,1),768,K6,1)
C
C        SAMPLE POINTS OF INTEREST (EVEN K PLANES)
C
         IF (K.EQ.14) THEN
            WRITE (4,111) MN4,THN,HZ(10,4)
            WRITE (4,111) MN5,THN,HZ(19,4)
            WRITE (4,111) MN6,THN,HX(22,18)
         ELSE
         END IF
C
```

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        IF (K.EQ.6) WRITE (4,111) MN1,THN,HX(18,18)
C
900     CONTINUE
        RETURN
        END
        SUBROUTINE APERT
        RETURN
        END
         SUBROUTINE AIRPLN
C
C ZEROES THE ELECTRIC FIELDS WITHIN THE F16 AIRCRAFT AND
C TANGENTIAL ELECTRIC FIELD COMPONENTS AT THE SURFACE
C
        COMMON /ARRAYS/ FLD (27,27),B1 (39)
C
C       EX ZEROED
C
        DO 1000 K=3,25
        CALL READMS (2,FLD(1,1),768,K)
C       WING
        IF (K.NE.3) GO TO 40
        FLD(18,9)=0.0
        FLD(19,9)=0.0
40      IF (K.NE.4) GO TO 50
        DO 41 I=17,19
41      FLD(I,9)=0.0
50      IF (K.LT.5.OR.K.GT.6) GO TO 70
        DO 51 I=16,19
51      FLD(I,9)=0.0
70      IF (K.LT.7.OR.K.GT.8) GO TO 90
        DO 71 I=15,19
        DO 71 J=9,10
71      FLD(I,J)=0.0
        FLD(23,9)=0.0
        FLD(24,9)=0.0
90      IF (K.NE.9) GO TO 100
        DO 91 I=14,19
        DO 91 J=9,10
91      FLD(I,J)=0.0
        DO 92 I=22,24
92      FLD(I,9)=0.0
100     IF (K.NE.10) GO TO 110
        DO 101 I=13,19
        DO 101 J=9,10
101     FLD(I,J)=0.0
        DO 102 I=21,24
102     FLD(I,9)=0.0
110     IF (K.NE.11) GO TO 120
        DO 111 I=11,23
        DO 111 J=9,10
111     FLD(I,J)=0.0
        DO 112 I=11,22
```

```
112   FLD(I,8)=0.0
C     MAIN FUSELAGE
120   IF (K.LT.12.OR.K.GT.15) GO TO 126
      DO 121 I=18,19
      DO 121 J=5,12
121   FLD(I,J)=0.0
C
C     FORWARD FUSELAGE
C
      DO 122 I=6,9
      DO 122 J=8,10
122   FLD(I,J)=0.0
      DO 123 I=8,9
      DO 123 J=11,12
123   FLD(I,J)=0.0
      FLD(7,11)=0.0
C     REAR FUSELAGE
      DO 124 I=20,22
124   FLD(I,6)=0.0
      DO 125 I=20,23
      DO 125 J=7,12
125   FLD(I,J)=0.0
126   IF (K.NE.12.OR.K.NE.15) GO TO 130
      DO 127 I=19,20
      DO 127 J=3,4
127   FLD (I,J)=0.0
       FLD(20,5)=0.0
130   IF (K.LT.13.OR.K.GT.14) GO TO 135
      FLD(24,9)=0.0
      FLD(24,10)=0.0
C     NOSE AND COCKPIT
      DO 131 I=4,5
      DO 131 J=8,9
131   FLD(I,J)=0.0
      FLD(5,10)=0.0
      FLD(6,11)=0.0
      FLD(7,12)=0.0
      DO 132 I=8,11
      DO 132 J=13,14
132   FLD(I,J)=0.0
      FLD(12,13)=0.0
      FLD(13,13)=0.0
      FLD(9,15)=0.0
C
C     RIGHT VERTICAL STABALIZER
C
135   IF (K.NE.13) GO TO 140
      DO 136 I=19,23
      DO 136 J=13,14
136   FLD(I,J)=0.0
      FLD(17,13)=0.0
      FLD(18,13)=0.0
```

```
140    IF (K.NE.14) GO TO 160
       DO 141 I=18,23
       DO 141 J=13,14
141    FLD(I,J)=0.0
       FLD(17,23)=0.0
       DO 142 I=20,23
       DO 142 J=15,19
142    FLD(I,J)=0.0
       FLD(20,15)=0.0
       FLD(20,16)=0.0
       DO 143 I=22,23
       DO 143 J=20,22
143    FLD(I,J)=0.0
       FLD(24,21)=0.0
       FLD(24,22)=0.0
       DO 144 I=23,24
       DO 144 J=23,24
144    FLD(I,J)=0.0
160    IF (K.NE.16) GO TO 170
       DO 161 I=11,22
       DO 161 J=8,10
161    FLD(I,J)=0.0
       FLD(23,9)=0.0
       FLD(23,10)=0.0
170    IF (K.NE.17) GO TO 180
C      WING
       DO 171 I=13,19
       DO 171 J=9,10
171    FLD(I,J)=0.0
C
C      RIGHT HORIZONTAL STABALIZER
C
       DO 172 I=21,24
172    FLD(I,9)=0.0
180    IF (K.NE.18) GO TO 190
       DO 181 I=14,19
       DO 181 J=9,10
181    FLD(I,J)=0.0
       DO 182 I=22,24
182     FLD(I,9)=0.0
190    IF (K.LT.19.OR.K.GT.20) GO TO 210
       DO 191 I=15,19
       DO 191 J=9,10
191    FLD(I,J)=0.0
       FLD(23,9)=0.0
       FLD(24,9)=0.0
210    IF (K.LT.21.OR.K.GT.22) GO TO 230
       DO 211 I=16,19
211    FLD(I,9)=0.0
230    IF (K.NE.23) GO TO 240
       DO 231 I=17,19
231    FLD(I,9)=0.0
```

```
240    IF (K.NE.24) GO TO 1000
       FLD(18,9)=0.0
       FLD(19,9)=0.0
C      STORE EX FIELDS BACK IN TO MASS STORAGE
1000   CALL WRITMS(2,FLD(1,1),768,K,1)
C        ZERO EY
       DO 2000 K=3,24
       L=K+27
       CALL READMS (2,FLD(1,1),768,L)
       IF (K.LT.7.OR.K.GT.10) GO TO 1110
       DO 1081 I=14,19
1081      FLD(I,10)=0.0
       IF (K.NE.9) GO TO 1100
       FLD(13,10)=0.0
1100   IF (K.NE.10) GO TO 1110
       FLD(12,10)=0.0
       FLD(13,10)=0.0
1110      IF (K.NE.11) GO TO 1120
       DO 1111 I=18,22
       DO 1111 J=9,10
1111      FLD(I,J)=0.0
       FLD(23,10)=0.0
C        MAIN FUSELAGE
1120      IF (K.LT.1".OR.K.GT.15) GO TO 1130
       DO 1121 I=9,19
       DO 1121 J=6,12
1121      FLD(I,J)=0.0
C      FWD FUSELAGE
       DO 1122 I=5,8
       DO 1122 J=9,10
1122      FLD(I,J)=0.0
       DO 1123 I=7,8
       DO 1123 J=11,12
1123      FLD(I,J)=0.0
       FLD(6,!1)=0.0
C      REAR FUSELAGE
       DO 1124 I=20,22
       DO 1124 J=7,12
1124      FLD(I,J)=0.0
       DO 1125 J=8,12
1125      FLD(23,J)=0.0
1130      IF (K.LT.13.OR.K.GT.14) GO TO 1126
       FLD(24,10)=0.0
1126      IF (K.NE.12.OR.K.NE.15) GO TO 1131
       DO 1127 I=18,20
       DO 1127 J=4,5
1127      FLD (I,J)=0.0
       FLD(20,6)=0.0
1131      IF (K.LT.13.OR.K.GT.14) GO TO 1135
       FLD(3,9)=0.0
       FLD(4,9)=0.0
       FLD(4,10)=0.0
```

```
        FLD(5,11)=0.0
        FLD(6,12)=0.0
        DO 1132 I=7,13
1132      FLD(I,13)=0.0
        DO 1133 I=7,11
1133      FLD(I,14)=0.0
        FLD(8,15)=0.0
        FLD(9,15)=0.0
1135      IF (K.NE.13) GO TO 1140
        DO 1136 I=16,23
1136      FLD(I,13)=0.0
        DO 1137 I=18,23
1137      FLD(I,14)=0.0
1140      IF (K.NE.14) GO TO 1160
        DO 1141 I=22,23
        DO 1141 J=13,24
1141      FLD(I,J)=0.0
        DO 1142 J=21,24
1142      FLD(24,J)=0.0
        DO 1143 J=20,22
1143      FLD(21,J)=0.0
        DO 1144 J=17,19
        DO 1144 I=20,21
1144      FLD(I,J)=0.0
        DO 1145 I=19,21
        DO 1145 J=15,16
1145      FLD(I,J)=0.0
        DO 1146 I=17,21
1146      FLD(I,14)=0.0
        DO 1147 I=16,21
1147      FLD(I,13)=0.0
1160      IF (K.NE.16) GO TO 1170
        DO 1161 I=18,22
        DO 1161 J=9,10
1161      FLD(I,J)=0.0
        FLD(23,10)=0.0
C       WING
1170      IF (K.NE.17) GO TO 1180
        DO 1171 I=12,19
1171      FLD(I,10)=0.0
1180      IF (K.NE.18) GO TO 1190
        DO 1181 I=13,19
1181      FLD(I,10)=0.0
1190      IF (K.LT.19.OR.K.GT.20) GO TO 2000
        DO 1191 I=14,19
1191      FLD(I,10)=0.0
C     STORE EY BACK TO MASS STORAGE
2000      CALL WRITMS(2,FLD(1,1),768,L,1)
C     EZ ZEROED
        DO 3000 K=3,24
          L=K+54
        CALL READMS(2,FLD(1,1),768,L)
```

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```
C       WING TIP
        IF (K.NE.4) GO TO 2050
        DO 2041        I=17,19
2041        FLD(I,9)=0.0
2050        IF (K.NE.5) GO TO 2060
        DO 2051 I=16,19
2051        FLD(I,9)=0.0
C       PLANE
2060        IF (K.LT.6.OR.K.GT.7) GO TO 2080
        DO 2061 I=15,19
2061        FLD(I,9)=0.0
C       WING
2080        IF (K.NE.8) GO TO 2090
        DO 2081 J=9,10
        DO 2081 I=14,19
2081        FLD(I,J)=0.0
C
C       RIGHT HAND STABALIZER
C
        DO 2082 I=22,24
2082        FLD(I,9)=0.0
2090        IF (K.NE.9) GO TO 2100
        DO 2091 I=14,19
        DO 2091 J=9,10
2091        FLD(I,J)=0.0
        DO 2092 I=22,24
2092        FLD(I,9)=0.0
2100        IF (K.NE.10) GO TO 2110
        DO 2101 I=13,19
        DO 2101 J=9,10
2101        FLD(I,J)=0.0
        DO 2102 I=21,24
2102        FLD(I,9)=0.0
2110        IF (K.NE.11) GO TO 2120
        DO 2111 I=12,24
2111        FLD(I,9)=0.0
        DO 2112 I=12,19
2112    FLD(I,10)=0.0
2120        IF (K.NE.12) GO TO 2130
        DO 2121 I=10,22
        DO 2121 J=8,10
2121        FLD(I,J)=0.0
        FLD(23,9)=0.0
        FLD(23,10)=0.0
2130        IF (K.LT.13.OR.K.GT.15) GO TO 2140
        DO 2131 I=9,19
        DO 2131 J=5,12
2131        FLD(I,J)=0.0
        DO 2132 I=5,8
        DO 2132 J=8,10
2132        FLD(I,J)=0.0
        DO 2133 I=7,8
```

```
          DO 2133 J=11,12
2133         FLD(I,J)=0.0
          FLD(6,11)=0.0
          DO 2134 I=20,22
          DO 2134 J=6,12
2134         FLD(I,J)=0.0
          DO 2135 J=7,12
2135         FLD(23,J)=0.0
2140         IF (K.NE.14) GO TO 2160
          FLD(24,9)=0.0
          FLD(24,10)=0.0
          DO 2141 I=3,4
          DO 2141 J=8,9
2141         FLD(I,J)=0.0
          FLD(4,10)=0.0
          FLD(5,11)=0.0
          FLD(6,12)=0.0
          DO 2142 I=7,11
          DO 2142 J=13,14
2142         FLD(I,J)=0.0
          FLD(12,13)=0.0
          FLD(13,13)=0.0
          FLD(8,15)=0.0
          FLD(9,15)=0.0
          DO 2143 I=16,23
2143         FLD(I,13)=0.0
          DO 2144 I=18,23
2144         FLD(I,14)=0.0
2160         IF (K.NE.16) GO TO 2170
          DO 2161 I=18,22
          DO 2161 J=8,10
2161         FLD(I,J)=0.0
          FLD(23,9)=0.0
          FLD(23,10)=0.0
2170         IF (K.NE.17) GO TO 2180
          DO 2171 I=12,24
2171         FLD(I,9)=0.0
          DO 2172 I=12,19
2172         FLD(I,10)=0.0
2180          IF (K.NE.18) GO TO 2190
          DO 2181 I=13,19
          DO 2181 J=9,10
2181         FLD(I,J)=0.0
          DO 2182 I=21,24
2182         FLD(I,9)=0.0
2190         IF (K.LT.19.OR.K.GT.20) GO TO 2210
          DO 2191 I=14,19
          DO 2191 J=9,10
2191         FLD(I,J)=0.0
          DO 2192 I=22,24
2192        FLD(I,9)=0.0
2210         IF (K.LT.21.OR.K.GT.22) GO TO 2230
```

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```
          DO 2211 I=15,19
2211         FLD(I,9)=0.0
2230         IF(K.NE.23) GO TO 2240
          DO 2231 I=16,19
2231         FLD(I,9)=0.0
2240      IF (K.NE.24) GO TO 3000
          DO 2241 I=17,19
2241         FLD(I,9)=0.0
C
C     STORE EZ BACK TO MASS STORAGE
C
3000         CALL WRITMS (2,FLD(1,1),768,L,1)
          RETURN
          END
```

Appendix B

Rymes' Code with Radiation Boundary Conditions

This appendix contains a complete listing of the
modified Rymes' code with the radiation boundary conditions
implemented. The compile time is 3.722 CPU seconds. The
run time for the first 100 nanoseconds was 4342 CPU seconds.
The F-16 is modeled in subroutine AIRPLN, as it is in the
previous appendix. The major changes include expansion of
the memory required and a complete rewrite of subroutine
SIGSET, now renamed RADBC. The code listing is complete as
implemented, and runs on a CDC Cyber 845. Improvements are
included which correct minor errors in code mechanics, and
also an improved source is implemented. The code compiles
on the Cyber 845 using FTN5, and runs with no problem when
suppressing ANSI errors. Continued runs require the changes
annotated in the code in addition to saving 'TAPE1' from the
previous run.

```
        PROGRAM RBC (OUTF16,TAPE6=OUTF16,TAPE 1)
C
C     THE MODIFIED RYMES 3-D CODE F16
C########
C     TO INCLUDE RADIATION BOUNDARY CONDITIONS DEVELOPED
C     DEVELOPED BY MEREWETHER AND INCORPORATED INTO THIS
C     CODE BY WILLIFORD AND HEBERT
C########
C
        COMMON /SET1/ NMAX,EPST,SIG0,C,TMUO,DELT
        COMMON /SET2/ ICAN,ICM1,ICP1,JCAN,JCM1,JCP1,KCAN,KCM1,KCP1
        COMMON /SET3/ DELX,DELY,DELZ
        COMMON /TIME/ TEN,THN
        COMMON /ARRAYS/ A1(27,27),B1(39),A2(27,27),B2(39),A3(27,27),
       +B3(39),A4(27,27),B4(39),A5(27,27),B5(39),A6(27,27),B6(39),
       +A7(27,27),B7(39),A8(27,27),B8(39),A9(27,27),B9(39),
       +A10(27,27),B10(39),A11(27,27),B11(39),A12(27,27),B12(39),
C########
       +A13(27,27),B13(39),A14(27,27),B14(39),A15(27,27),B15(39),
       +A16(27,27),B16(39),A17(27,27),B17(39),A18(27,27),B18(39),
       +A19(27,27),B19(39),A"0(27,27),B20(39)
C
        DIMENSION INDEX(352)
        CALL OPENMS(1,INDEX,352,0)
C########
C
C     READ INPUT DATA
C
        CALL SETUP
C
C     ZERO THE FIELDS INITIALLY.
C     PROGRAM USES A MASTER STORAGE FILE TO STORE FIELDS AND CONDUCTIVITY
C     OF EACH LATTICE POINT. INDEX K GOES FROM 1 TO 27.
C     EX    K
C     EY    K+27
C     EZ    K+54(27*2)
C     HX    K+81(27*3)
C     HY    K+108(27*4)
C     HZ    K+135(27*5)
C     SIG   K+162(27*6)
C########
C     HXTM2  K+189(27*7)
C     HYTM2  K+216(27*8)
C     HZTM2  K+243(27*9)
C     C1     K+270(27*10)
C     C2     K+297(27*11)
C     C3     K+324(27*12)
C########
C############DELETE FROM HERE TO STOP DELETE########
C              TO REMOVE THE ZEROING OF TAPE1
C              FOR CONTINUED RUNS BEYOND THE
C              INITIAL TMAX STOPING TIME
```

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```
C*************************************************
      DO 100 I=1,27
      DO 100 J=1,27
100   A1(I,J)=0.0
C*******
      DO 200 K=1,351
C*******
200   CALL WRITMS(1,A1(1,1),768,K,0)
C
C************STOP DELETE HERE GO TO THN=    *********
C
C
C     PRESET THE CONDUCTIVITY ARRAY
C
      CALL RADBC
C
C     TIME STEP LOOP
C
      DO 1000 N=1,NMAX
      CALL APERT
C
C     COMPUTE TIME CONSTANTS
C
C************FOR CONTINUED RUNS BEYOND TMAX**********
C           ADD THE STOPPING TIME FROM PREVIOUS
C           RUNS TO THN AND TEN PLUS 1/2 OF DELTA T
C
C       EXAMPLE
C
C      AFTER FIRST RUN
C
C        THN=DELT*(FLOAT(N)-1.0)+1.00183E-7
C        TEN=DELT*(FLOAT(N)-.5)+1.00183E-7
C*************************************************
      THN=DELT*(FLOAT(N)-1.0)
      TEN=DELT*(FLOAT(N)-.5)
C
C     ADVANCE THE H-FIELDS BY Z-PLANES
C
      CALL HADV
C
C     ADVANCE THE E-FIELDS BY Z-PLANES
C
      CALL EADV
1000  CONTINUE
C
C     END OF TIME LOOP
C
      CALL CLOSMS(1)
      STOP
      END
      SUBROUTINE SETUP
```

```
C     CODE USES A UNIFORM GRID.
C
      COMMON /SET1/ NMAX,EPST,SIGO,C,TMUO,DELT
      COMMON /SET2/ ICAN,ICM1,ICP1,JCAN,JCM1,JCP1,KCAN,KCM1,KCP1
      COMMON /SET3/DELX,DELY,DELZ
C*******
C
C
C
C*******
C     INPUT DATA PROVIDED BY USER.
C
C*******
C     SET SIGO=0.0 TO STOP ABSORPTION BC
      DATA C,EPSO,EPSR,XMUO,SIGO/3.0E8,8.8542E-12,1.0,1.2566E-6,0.0/
C*******
      DATA ICP1,JCP1,KCP1/27,27,27/
      DATA DELX,DELY,DELZ/.69,.22,.45/
      DATA TMAX/1.E-7/
C
      ICAN=ICP1-1
      ICM1=ICAN-1
      JCAN=JCP1-1
      JCM1=JCAN-1
      KCAN=KCP1-1
      KCM1=KCAN-1
C
C     VERIFY THAT ICP1,JCP1,KCP1 ARE ODD.
C
      IF(ICAN.EQ.2*(ICAN/2).AND.JCAN.EQ.2*(JCAN/2).AND.
     +KCAN.EQ.2*(KCAN/2))GO TO 1
      PRINT *,' THE NUMBER OF GRID POINTS MUST BE ODD '
      STOP
1     CONTINUE
C
C     DELT IS THE TIME INCREMENT (IT SATISFIES COURANT CONDITION).
C     NMAX IS THE TOTAL NUMBER OF TIME INCREMENTS FIELDS WOULD BE ADVANCED.
C
      DELT=AMIN1(DELX,DELY,DELZ)/(2.*C)
      NMAX=TMAX/DELT
      EPST=EPSO*EPSR/DELT
      TMUO=DELT/XMUO
      RETURN
      END
      SUBROUTINE RADBC
C
C     SIG(I,J) AT K1=K+162 IS THE CONDUCTIVITY AT THE POINT (X(I),Y(J),Z(K)).
C     X(I)=(I-.5)*DELX, Y(J)=(J-.5)*DELY, Z(K)=(K-.5)*DELZ
C
C*******
      REAL RN(27,27),RNP(27,27),THETA,RCON
      COMMON /ARRAYS/ SIG(27,27),B1(39)
```

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```
     +A13(27,27),B13(39),A14(27,27),B14(39),C1(27,27),B15(39),
     +C2(27,27),B16(39),C3(27,27),B17(39),A18(27,27),B18(39),
     +A19(27,27),B19(09),A20(27,27),B20(39)
      COMMON /SET3/ DELX,DELY,DELZ
C
C
C********
      COMMON /SET1/ NMAX,EPST,SIG0,C,TMUD,DELT
      COMMON /SET2/ ICAN,ICM1,ICP1,JCAN,JCM1,JCP1,KCAN,KCM1,KCP1
C
C
C      PRESET THE CONDUCTIVITY HERE IF NEEDED
C*******
C
C      CALCULATE GEOMETRIC CONSTANTS FOR RADBC
C
C      FINDING CENTER OF SHIFTED COORDINATE SYSTEM
      IX0=ICAN/2+1
      IY0=JCAN/2+1
      IZ0=KCAN/2+1
C
      DO 50 K=1,KCAN
      K11=K+270
      K12=K+297
      K13=K+324
C
      CALL READMS (1,C1(1,1),768,K11)
      CALL READMS (1,C2(1,1),768,K12)
      CALL READMC (1,C3(1,1),768,K13)
      IF (K.EQ.2.OR.K.EQ.KCAN) THEN
C
C      FACE
      KN=IABS(K-IZ0)
      KNP=KN+1
      DO 60 I=1,ICAN
      DO 70 J=1,JCAN
C
      IN=IABS(I-IX0)
      JN=IABS(J-IY0)
C
      RN(I,J)=SQRT((FLOAT(IN)*DELX)**2.0+(FLOAT(JN)*DELY)**2.0
     $+(FLOAT(KN)*DELZ)**2.0)
      RNP(I,J)=SQRT((FLOAT(IN)*DELX)**2.0+(FLOAT(JN)*DELY)**2.0
     $+(FLOAT(KNP)*DELZ)**2.0)
      THETA=(IFIX((RNP(I,J)-RN(I,J))/(DELZ)+0.5))-
     $((RNP(I,J)-RN(I,J))/(DELZ))
C
      RCOM=RN(I,J)/(2.0*RNP(I,J))
C
      C1(I,J)=RCOM*(THETA*(THETA-1.0))
      C2(I,J)=RCOM*2.0*(1.0-(THETA**2.0))
      C3(I,J)=RCOM*THETA*(THETA+1.0)
```

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```fortran
70      CONTINUE
60      CONTINUE
C
        ELSE
C       SIDES OF K-PLANES
        KN=IABS(K-IZ0)
C
        ICM2=ICAN-2
        JCM2=JCAN-2
C       SIDES OF I=2 & ICAN
        DO 80 I=2,ICAN,ICM2
        DO 90 J=1,JCAN
C
        IN=IABS(I-IX0)
        INP=IN+1
        JN=IABS(J-IY0)
C
        RN(I,J)=SQRT((FLOAT(IN)*DELX)**2.0+(FLOAT(JN)*DELY)**2.0
       $+(FLOAT(KN)*DELZ)**2.0)
        RNP(I,J)=SQRT((FLOAT(INP)*DELX)**2.0+(FLOAT(JN)*DELY)**2.0
       $+(FLOAT(KN)*DELZ)**2.0)
C
        THETA=(IFIX(((RNP(I,J)-RN(I,J))/(DELX)+0.5))-
       $((RNP(I,J)-RN(I,J))/(DELX))
        RCOM=RN(I,J)/(2.0*RNP(I,J))
C
        C1(I,J)=RCOM*(THETA*(THETA-1.0))
        C2(I,J)=RCOM*2.0*(1.0-(THETA**2.0))
        C3(I,J)=RCOM*(THETA*(THETA+1.0))
C
90      CONTINUE
80      CONTINUE
C       SIDES AT J=2 & JCAN
        DO 100 J=2,JCAN,JCM2
        DO 110 I=1,ICAN
C
        IN=IABS(I-IX0)
        JN=IABS(J-IY0)
        JNP=JN+1
C
        RN(I,J)=SQRT((FLOAT(IN)*DELX)**2.0+(FLOAT(JN)*DELY)**2.0
       $+(FLOAT(KN)*DELZ)**2.0)
        RNP(I,J)=SQRT((FLOAT(IN)*DELX)**2.0+(FLOAT(JNP)*DELY)**2.0
       $+(FLOAT(KN)*DELZ)**2.0)
C
        THETA=(IFIX(((RNP(I,J)-RN(I,J))/(DELY)+0.5))-
       $((RNP(I,J)-RN(I,J))/(DELY))
        RCOM=RN(I,J)/(2.0*RNP(I,J))
C
        C1(I,J)=RCOM*(THETA*(THETA-1.0))
        C2(I,J)=RCOM*2.0*(1.0-(THETA**2.0))
        C3(I,J)=RCOM*(THETA*(THETA+1.0))
```

100

```
110    CONTINUE
100    CONTINUE
C
       END IF
C
       CALL WRITMS (1,C1(1,1),768,K11,1)
       CALL WRITMS (1,C2(1,1),768,K12,1)
       CALL WRITMS (1,C3(1,1),768,K13,1)
C
50     CONTINUE
.C
 C
C********
C
       RETURN
       END
       SUBROUTINE EADV
C
C      THIS SUBROUTINE ADVANCES THE E-FIELDS  TWO Z-PLANES AT A TIME.
C      RECORDS OF H-FIELDS FOR TWO SUCCESIVE Z-PLANES MUST BE KEPT IN
C      ORDER TO TAKE DERIVATIVES IN THE Z-DIRECTION.
C      RECORDS OF SIG FOR TWO SUCCESIVE Z-PLANES MUST BE KEPT IN ORDER TO TAKE
C      AVERAGES IN THE Z-DIRECTION.
C
       COMMON /SET1/NMAX,EPST,SIGO,C,TMUO,DELT
       COMMON /SET2/ ICAN,ICM1,ICP1,JCAN,JCM1,JCP1,KCAN,KCM1,KCP1
       COMMON /SET3/ DELX,DELY,DELZ
       COMMON /TIME/ TEN,THN
       COMMON /ARRAYS/ EX(27,27),B1(39),EY(27,27),B2(39),EZ(27,27),
      +B3(39),HXA(27,27),B4(39),HXB(27,27),B5(39),HYA(27,27),B6(39),
      +HYB(27,27),B7(39),HZA(27,27),B8(39),HZB(27,27),B9(39),
      +SIGA(27,27),B10(39),SIGB(27,27),B11(39)
C
C      ADVANCE E-FIELDS BY Z-PLANES
C      READ IN FIRST H-PLANES
C
       CALL READMS(1,HXA(1,1),768,82)
       CALL READMS(1,HYA(1,1),768,109)
C
C      DO FOR ALL Z-PLANES
C
       MN8=8
       MN9=9
       MN10=10
       DO 1000 KLOOP=1,KCAN,2
       K=KLOOP
       KP1=K+1
       K2=K+27
       K3=K+54
       K4=K+82
       K5=K+109
       K6=K+135
```

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```
      K7=K+162
C
C     READ IN SECOND H-PLANES AND OLD E-FIELDS
C
      CALL READMS(1,EX(1,1),768,K)
      CALL READMS(1,EY(1,1),768,K2)
      CALL READMS(1,EZ(1,1),768,K3)
      CALL READMS(1,HXB(1,1),768,K4)
      CALL READMS(1,HYB(1,1),768,K5)
      CALL READMS(1,HZA(1,1),768,K6)
      CALL READMS(1,SIGA(1,1),768,K7)
C
      DO 200 J=1,JCAN
      JP1=J+1
      DO 200 I=2,ICAN
C
C     SIG(IX0,Y,Z)=.5*(SIG(X-DELX,Y,Z)+SIG(X,Y,Z))
C     SIG(X,IY0,Z)=.5*(SIG(X,Y-DELY,Z)+SIG(X,Y,Z))
C     SIG(X,Y,IZ0)=.5*(SIG(X,Y,Z-DELZ)+SIG(X,Y,Z))
C
      SIG2=.25*(SIGA(I,J)+SIGA(I-1,J))
      A=EPST-SIG2
      B=1./(EPST+SIG2)
      EX(I,J)=(A*EX(I,J)+(HZA(I,JP1)-HZA(I,J))/DELY -
     +(HYB(I,J)-HYA(I,J))/DELZ)*B
200   CONTINUE
      DO 300 I=1,ICAN
      IP1=I+1
      DO 300 J=2,JCAN
      SIG2=.25*(SIGA(I,J-1)+SIGA(I,J))
      A=EPST-SIG2
      B=1./(EPST+SIG2)
      EY(I,J)=(A*EY(I,J)+(HXB(I,J)-HXA(I,J))/DELZ -
     +(HZA(IP1,J)-HZA(I,J))/DELX)*B
300   CONTINUE
C
C     WRITE NEW EX,EY PLANES TO MASS STORAGE
C
      CALL WRITMS(1,EX(1,1),768,K,1)
      CALL WRITMS(1,EY(1,1),768,K2,1)
      IF (K.EQ.1)GO TO 450
      DO 400 I=1,ICAN
      IP1=I+1
      DO 400 J=1,JCAN
      JP1=J+1
      SIG2=.25*(SIGA(I,J)+SIGB(I,J))
      A=EPST-SIG2
      B=1./(EPST+SIG2)
      EZ(I,J)=(A*EZ(I,J)+(HYA(IP1,J)-HYA(I,J))/DELX-
     +(HXA(I,JP1)-HXA(I,J))/DELY)*B
400   CONTINUE
C
```

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```
C      WRITE NEW EZ PLANE TO MASS STORAGE
C
       CALL WRITMS(1,EZ(1,1),768,K3,1)
C
C      SAMPLE POINTS OF INTEREST(ODD K PLANES)
C
111       FORMAT (I4,2(1X,1P1E11.4))
112       FORMAT (I4,2(1X,1P1E11.4),2(/))
C
C
450    CONTINUE
       K=KP1
       KP1=K+1
       K2=K2+1
       K3=K3+1
       K4=K4+1
       K5=K5+1
       K6=K6+1
       K7=K7+1
C
C      READ IN SECOND OLD E-PLANES AND NEXT H-PLANES OVER A PLANE
C
       CALL READMS(1,EX(1,1),768,K)
       CALL READMS(1,EY(1,1),768,K2)
       CALL READMS(1,EZ(1,1),768,K3)
       CALL READMS(1,HXA(1,1),768,K4)
       CALL READMS(1,HYA(1,1),768,K5)
       CALL READMS(1,HZB(1,1),768,K6)
       CALL READMS(1,SIGB(1,1),768,K7)
       DO 600 J=1,JCAN
       JP1=J+1
       DO 600 I=2,ICAN
       SIG2=.25*(SIGB(I,J)+SIGB(I-1,J))
       A=EPST-SIG2
       B=1./(EPST+SIG2)
       EX(I,J)=(A*EX(I,J)+(HZB(I,JP1)-HZB(I,J))/DELY -
      +(HYA(I,J)-HYB(I,J))/DELZ)*B
600    CONTINUE
       DO 700 I=1,ICAN
       IP1=I+1
       DO 700 J=2,JCAN
       SIG2=.25*(SIGB(I,J-1)+SIGB(I,J))
       A=EPST-SIG2
       B=1./(EPST+CIG2)
       EY(I,J)=(A*EY(I,J)+(HXA(I,J)-HXB(I,J))/DELZ -
      +(HZB(IP1,J)-HZB(I,J))/DELX)*B
700    CONTINUE
       DO 800 I=1,ICAN
       IP1=I+1
       DO 800 J=1,JCAN
       JP1=J+1
       SIG2=.25*(SIGB(I,J)+SIGA(I,J))
```

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```fortran
      A=EPST-SIG2
      B=1./(EPST+SIG2)
      EZ(I,J)=(A*EZ(I,J)+(HYB(IP1,J)-HYB(I,J))/DELX -
     +(HXB(I,JP1)-HXB(I,J))/DELY)*B
800   CONTINUE
C
C     WRITE NEW EX,EY,EZ PLANES TO MASS STORAGE
C
      CALL WRITMS(1,EX(1,1),768,K,1)
      CALL WRITMS(1,EY(1,1),'68,K2,1)
      CALL WRITMS(1,EZ(1,1),768,K3,1)
C
C     SAMPLE POINTS OF INTEREST (EVEN K PLANES)
C
      IF (K.EQ.10) WRITE (6,111) MN8,TEN,EY(17,11)
      IF (K.EQ.18) WRITE (6,112) MN10,TEN,EY(17,11)
C
      IF (K.EQ.14)  THEN
        WRITE (6,111) MN9,TEN,EI(15,13)
      ELSE
      END IF
C
1000  CONTINUE
C
C     ZERO THE ELECTRIC FIELD WITHIN THE METAL COMPONENTS OF AIRCRAFT.
C
      CALL AIRPLN
      RETURN
      END
      SUBROUTINE HADV
C
C     THIS SUBROUTINE ADVANCES THE H-FIELDS TWO Z-PLANES AT A TIME.
C     RECORDS OF E-FIELDS FOR TWO SUCCESIVE PLANES MUST BE KEPT IN ORDER TO TAKE
C     DERIVATIVES IN THE Z-DIRECTION.
C########
C     ALSO MOST MODIFICATIONS FOR THE RADIATION
C     BOUNDARY CONDITIONS WERE PLACED HERE
C########
C
      COMMON /SET1/ NMAX,EPST,SIG0,C,TMU0,DELT
      COMMON /SET2/ ICAN,ICM1,ICP1,JCAN,JCM1,JCP1,KCAN,KCM1,KCP1
      COMMON /SET3/ DELX,DELY,DELZ
      COMMON /TIME/ TEN,THN
      COMMON /ARRAYS/ EXA(27,27),B1(39),EXB(27,27),B2(39),
     +EYA(27,27),B3(39),EYB(27,27),B4(39),EZA(27,27),B5(39),
     +EZB(27,27),B6(39),HX(27,27),B7(39),HY(27,27),B8(39),
     +HZ(27,27),B9(39),
C########
     +A10(27,27),B10(39),A11(27,27),B11(39),HXTM2(27,27),B12(39),
     +HYTM2(27,27),B13(39),HZTM2(27,27),B14(39),C1(27,27),B15(39),
     +C2(27,27),B16(39),C3(27,27),B17(39),HXKM1(27,27),B18(39),
     +HYKM1(27,27),B19(39),HZKM1(27,27),B20(39)
```

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```
          REAL HXTM1(27,27),HYTM1(27,27),HZTM1(27,27)
C
C*******
C
C
C      DO FOR ALL Z-PLANES
          MN1=1
          MN2=2
          MN3=3
          MN4=4
         MN5=5
         MN6=6
         MN7=7
C
       DO 900 KLOOP=1,KCAN,2
       K=KLOOP
       KM1=K-1
       K2=K+27
       K3=K+54
       K4=K+81
       K5=K+108
       K6=K+135
C*******
       K10=K+243
       K11=K+270
       K12=K+297
       K13=K+324
       CALL READMS (1,HZTM2(1,1),768,K10)
       CALL READMS (1,C1(1,1),768,K11)
       CALL READMS (1,C2(1,1),768,K12)
       CALL READMS (1,C3(1,1),768,K13)
C*******
       CALL READMS(1,EXB(1,1),768,K)
       CALL READMS(1,EYB(1,1),768,K2)
       CALL READMS(1,HZ(1,1),768,K6)
       IF (K.EQ.1)GO TO 350
C*******
       K8=K+189
       K9=K+216
       CALL READMS(1,HXTM2(1,1),768,K8)
       CALL READMS (1,HYTM2(1,1),768,K9)
C*******
       CALL READMS(1,EZB(1,1),768,K3)
       CALL READMS(1,HX(1,1),768,K4)
       CALL READMS(1,HY(1,1),768,K5)
       DO 200 J=2,JCAN
       DO 200 I=1,ICAN
C*******
       HXTM1(I,J)=HX(I,J)
C*******
       HX(I,J)=HX(I,J)+TMUO*((EYB(I,J)-EYA(I,J))/DELZ -
      +(EZB(I,J)-EZB(I,J-1))/DELY)
```

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```
200   CONTINUE
      DO 300 I=1,ICM1
      IP1=I+1
      DO 300 J=1,JCAN
C*******
      HYTM1(IP1,J)=HY(IP1,J)
C*******
      HY(IP1,J)=HY(IP1,J)+TMUO*((EZB(IP1,J)-EZB(I,J))/DELX -
     +(EXB(IP1,J)-EXA(IP1,J))/DELZ)
300   CONTINUE
C
C     APPROXIMATES H FIELDS IN PLANE PERPENDICULAR TO WIRE
C     BY H=I/2*PI*R.
C       SOURCE FUNCTION,ODD K REFERENCE PLANES, HY
C     CURRENT PULSE MOVING IN X DIRECTION ATTACHES TO THE NOSE OF THE AIRPLANE
C     AT (X,Y,Z)=(3,9,15), EXITS BY THE TAIL AT (X,Y,Z)=(25,10,15).
C      AT TIME T=0.0 PULSE IS LOCATED AT X0(3).
C
      IF(K.NE.15)GO TO 1
      DO 10 I=2,3,1
      TPULSE=THN-.69*(FLOAT(I)-3.)/C
      IF(TPULSE.LE.0.0)GO TO 10
C
        X=EXP(-3.5E04*TPULSE)-EXP(-2.625E7*TPULCE)
C
        HYS=7.07E3*X
      HY(I,9)=-HYS
10    CONTINUE
      DO 30 I=25,26,1
       TPULSE=THN-.69*(FLOAT(I)-3.0)/C
      IF(TPULSE.LE.0.0)GO TO 30
        X=EXP(-3.5E4*TPULSE)-EXP(-2.625E7*TPULSE)
        HYS=7.07E3*X
      HY(I,10)=-HYS
30    CONTINUE
1     CONTINUE
C*******
C     SIDES WHEN I=1 &ICP1
      ICM2=ICAN-2
      DO 310 I=2,ICAN,ICM2
      DO 320 J=1,JCAN
          IF (I.EQ.2)THEN
                  IB=1
          ELSE
                  IB=ICAN+1
          END IF
      HY(IB,J)=C1(I,J)*HYTM2(I,J)+C2(I,J)*HYTM1(I,J)+C3(I,J)*HY(I,J)
      HYTM2(I,J)=HYTM1(I,J)
      IF (J.GE.2) THEN
      HZ(IB,J)=C1(I,J)*HZTM2(I,J)+C2(I,J)*HZTM1(I,J)+C3(I,J)*HZ(I,J)
      HZTM2(I,J)=HZTM1(I,J)
      ELSE
```

```fortran
         END IF
320   CONTINUE
310   CONTINUE
C     SIDES WHEN J=1 & JCP1
      JCM2=JCAN-2
      DO 330 J=2,JCAN,JCM2
      DO 340 I=!,ICAN
         IF (J.EQ.2) THEN
               JB=1
         ELSE
               JB=JCAN+1
         END IF
      HX(I,JB)=C1(I,J)*HXTM2(I,J)+C2(I,J)*HXTM1(I,J)+C3(I,J)*HX(I,J)
      HXTM2(I,J)=HXTM1(I,J)
      IF (I.GE.2) THEN
      HZ(I,JB)=C1(I,J)*HZTM2(I,J)+C2(I,J)*HZTM1(I,J)+C3(I,J)*HZ(I,J)
      HZTM2(I,J)=HZTM1(I,J)
      ELSE
      END IF
340   CONTINUE
330   CONTINUE
      HZ(1,1)=HZ(2,1)
      HZ(1,27)=HZ(2,27)
      HZ(27,1)=HZ(27,2)
      HZ(27,*7)=HZ(27,26)
C*******
C
C     WRITE NEW HX,HY PLANES TO MASS STORAGE
C
      CALL WRITMS(1,HX(1,1),768,K4,1)
      CALL WRITMS(1,HY(1,1),768,K5,1)
C*******
      CALL WRITMS(1,HZ(1,1),768,K6,1)
      CALL WRITMS(1,HXTM2(1,1),768,K8,1)
      CALL WRITMS(1,HYTM2(1,1),768,K9,1)
      CALL WRITMS(1,HZTM2(1,1),768,K10,1)
C*******
350   CONTINUE
      DO 400 I=1,ICM1
      IP1=I+1
      DO 400 J=1,JCM1
      JP1=J+1
C*******
      HZTM1(IP1,JP1)=HZ(IP1,JP1)
C*******
      HZ(IP1,JP1)=HZ(IP1,JP1)+TMUD*((EXB(IP1,JP1)-EXB(IP1,J))/DELY -
     +(EYB(IP1,JP1)-EYB(I,JP1))/DELX)
400   CONTINUE
C*******
C     SIDES I=1 & ICP1
      ICM2=ICAN-2
      DO 610 I=2,ICAN,ICM2
```

```
      DO 620 J=2,JCAN
          IF (I.EQ.2) THEN
                  IB=1
          ELSE
                  IB=ICAN+1
          END IF
C
      HZ(IB,J)=C1(I,J)*HZTM2(I,J)+C2(I,J)*HZTM1(I,J)+C3(I,J)*HZ(I,J)
      HZTM2(I,J)=HZTM1(I,J)
620   CONTINUE
610   CONTINUE
      JCM2=JCAN-2
C     SIDES J=1  & JCP1
      DO 630 J=2,JCAN,JCM2
      DO 640 I=2,ICAN
          IF (J.EQ.2) THEN
                  JB=1
          ELSE
                  JB=JCAN+1
          END IF
      HZ(I,JB)=C1(I,J)*HZTM2(I,J)+C2(I,J)*HZTM1(I,J)+C3(I,J)*HZ(I,J)
      HJTM2(I,J)=HZTM1(I,J)
640   CONTINUE
630   CONTINUE
      HZ(1,1)=HZ(2,1)
      HZ(1,27)=HZ(2,27)
      HZ(27,1)=HZ(27,2)
      HZ(27,27)=HZ(27,26)
C     WRITE NEW HZ PLANE TO MASS STORAGE
C
      CALL WRITMS(1,HZ(1,1),768,K6,1)
      CALL WRITMS(1,HZTM2(1,1),768,K10,1)
C*******
C
C     SAMPLE POINTS OF INTEREST (ODD K PLANES)
C
      IF (K.EA.13) WRITE(6,111) MR2,THN,HZ(4,10)
      IF (K.EQ.13) WRITE(6,111) MN3,THN,HZ(24,11)
      IF (K.EQ.23) WRITE(6,111) MN7,THN,HX(18,10)
C
111   FORMAT (I4,2(1X,1P1E11.4))
C
      K=K+1
      KM1=K-1
      K2=K2+1
      K3=K3+1
      K4=K4+1
      K5=K5+1
      K6=K6+1
C*******
      K8=K+189
      K9=K+216
```

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```
            K10=K+243
            K11=K+270
            K12=K+297
            K13=K+324
            CALL READMS(1,HXTM2(1,1),768,K8)
            CALL READMS(1,HYTM2(1,1),768,K9)
            CALL READMS(1,HZTM2(1,1),768,K1 )
            CALL READMS(1,C1(1,1),768,K11)
            CALL READMS(1,C2(1,1),768,K12)
            CALL READMS(1,C3(1,1),768,K13)
C     FACE
            IF (K.EQ.2.OR.K.EQ.KCAN) THEN
                    IF (K.EQ.2) THEN
                                    KM1X=K+80
                                    KM1Y=K+107
                                    KM1Z=K+134
            CALL READMS (1,HXKM1(1,1),768,KM1X)
            CALL READMS (1,HYKM1(1,1),768,KM1Y)
            CALL READMS (1,HZKM1(1,1),768,KM1Z)
                    ELSE
                                    KM1X=K+82
                                    KM1Y=K+109
                                    KM1Z=K+136
            CALL READMS (1,HXKM1(1,1),768,KM1X)
            CALL READMS (1,HYKM1(1,1),768,KM1Y)
            CALL READMS (1,HZKM1(1,1),768,KM1Z)
                    END IF
            ELSE
            END IF
C*******
C
C     READ IN NEXT PLANES OF E AND H
C
            CALL READMS(1,EXA(1,1),768,K)
            CALL READMS(1,EYA(1,1),768,K2)
            CALL READMS(1,EZA(1,1),768,K3)
            CALL READMS(1,HX(1,1),768,K4)
            CALL READMS(1,HY(1,1),768,K5)
            CALL READMS(1,HZ(1,1),768,K6)
            DO 600 J=1,JCM1
            JP1=J+1
            DO 600 I=1,ICAN
C*******
            HXTM1(I,JP1)=HX(I,JP1)
C*******
            HX(I,JP1)=HX(I,JP1)+TMUO*((EYA(I,JP1)-EYB(I,JP1))/DELZ -
           +(EZA(I,JP1)-EZA(I,J))/DELY)
600         CONTINUE
            DO 700 I=1,ICM1
            IP1=I+1
            DO 700 J=1,JCAN
C*******
```

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```
      HYTM1(IP1,J)=HY(IP1,J)
C*******
      HY(IP1,J)=HY(IP1,J)+TMUO*((EZA(IP1,J)-EZA(I,J))/DELX -
     +(EXA(IP1,J)-EXB(IP1,J))/DELZ)
700   CONTINUE
C
C     SOURCE FUNCTION, EVEN K REFERENCE PLANES, HY
C
      IF (K.NE.14)GO TO 2
      DO 20 I=2,3,1
      TPULSE=THN-.69*(FLOAT(I)-3.)/C
      IF (TPULSE.LE.0.0)GO TO 20
        X=EXP(-3.5E4*TPULSE)-EXP(-2.625E7*TPULSE)
        HYS=7.07E3*X
      HY(I,9)=+HYS
20    CONTINUE
      DO 40 I=25,26,1
      TPULSE=THN-.69*(FLOAT(I)-3.)/C
      IF (TPULSE.LE.0.0)GO TO 40
        X-EXP(-3.5E4*TPULSE)-EXP(-2.625E7*TPULSE)
        HYS=7.07E3*X
      HY(I,10)=HYS
40    CONTINUE
2     CONTINUE
      DO 800 I=1,ICM1
      IP1=I+1
      DO 800 J=1,JCM1
      JP1=J+1
C*******
      HZTM1(IP1,JP1)=HZ(IP1,JP1)
C*******
      HZ(IP1,JP1)=HZ(IP1,JP1)+TMUO*((EXA(IP1,JP1)-EXA(IP1,J))/DELY -
     +(EYA(IP1,JP1)-EYA(I,JP1))/DELX)
800   CONTINUE
C
C
C     SOURCE FUNCTION, EVEN K REFERENCE PLANE, HZ
      IF(K.NE.14)GO TO 4
      DO 60 I=2,3,1
      TPULSE=THN-.69*(FLOAT(I)-3.)/C
      IF(TPULSE.LE.0.0)GO TO 60
        X=(EXP(-3.5E4*TPULSE)-EXP(-2.625E7*TPULSE))
        HZS=1.447E4*X
      HZ(I,9)=-HZS
      HZ(I,10)=HZS
60    CONTINUE
      DO 80 I=25,26,1
      TPULSE=THN-.69*(FLOAT(I)-3.)/C
      IF(TPULSE.LE.0.0)GO TO 80
        X=(EXP(-3.5E4*TPULSE)-EXP(-2.625E7*TPULSE))
        HZS=1.447E4*X
      HZ(I,10)=-HZS
```

110

```
          HZ(I,11)=HZS
80        CONTINUE
4         CONTINUE
C********
C     FACE
          IF (K.EQ.2.OR.K.EQ.KCAN)THEN
                  DO 210 I=2,ICAN
                  DO 220 J=2,JCAN
      HXKM1(I,J)=C1(I,J)*HXTM2(I,J)+C2(I,J)*HXTM1(I,J)+C3(I,J)*HX(I,J)
      HXTM2(I,J)=HXTM!(I,J)
      HYKM1(I,J)=C1(I,J)*HYTM2(I,J)+C2(I,J)*HYTM1(I,J)+C3(I,J)*HY(I,J)
      HYTM2(I,J)=HYTM1(I,J)
      HZKM1(I,J)=C1(I,J)*HZTM2(I,J)+C2(I,J)*HZTM1(I,J)+C3(I,J)*HZ(I,J)
      HZTM2(I,J)=HZTM!(I,J)
220   CONTINUE
210   CONTINUE
C     EDGES OF FACES
      ICM2=ICAN-2
      DO 410 I=2,ICAN,ICM2
      DO 420 J=2,JCAN
          IF (I.EQ.2) THEN
                  IB=1
          ELSE
                  IB=ICAN+1
          END IF
      HXKM1(IB,J)=HXKM1(I,J)
420   CONTINUE
410   CONTINUE
      JCM2=JCAN-2
      DO 430 J=2,JCAN,JCM2
      DO 440 I=2,ICAN
          IF (J.EQ.2) THEN
                  JB=1
          ELSE
                  JB=JCAN+1
          END IF
      HYKM1(I,JB)=HYKM1(I,J)
440   CONTINUE
430   CONTINUE
      CALL WRITMS(1,HXKM1(1,1),768,KM1X,1)
      CALL WRITMS(1,HYKM1(1,1),768,KM1Y,1)
      CALL WRITMS(1,HZKM1(1,1),768,KM1Z,1)
          ELSE
          END IF
      ICM2=ICAN-2
C     SIDED I= 1 & ICP1
      DO 230 I=2,ICAN,ICM2
      DO 240 J=1,JCAN
          IF (I.EQ.2) THEN
                  IB=1
          ELSE
                  IB=ICAN+1
```

111

```fortran
            END IF
      HY(IB,J)=C1(I,J)*HYTM2(I,J)+C2(I,J)*HYTM1(I,J)+C3(I,J)*HY(I,J)
      HYTM2(I,J)=HYTM1(I,J)
      IF (J.GE.2) THEN
      HZ(IB,J)=C1(I,J)*HZTM2(I,J)+C2(I,J)*HZTM1(I,J)+C3(I,J)*HZ(I,J)
      HZTM2(I,J)=HZTM1(I,J)
      ELSE
      END IF
240   CONTINUE
230   CONTINUE
      JCM2=JCAN-2
      DO 250 J=2,JCAN,JCM2
      DO 260 I=1,ICAN
         IF (J.EQ.2) THEN
                 JB=1
         ELSE
                 JB=JCAN+1
         END IF
      HX(I,JB)=C1(I,J)*HXTM2(I,J)+C2(I,J)*HXTM1(I,J)+C3(I,J)*HX(I,J)
      HXTM2(I,J)=HXTM1(I,J)
      IF (I.GE.2) THEN
      HZ(I,JB)=C1(I,J)*HZTM2(I,J)+C2(I,J)*HZTM1(I,J)+C3(I,J)*HZ(I,J)
      HZTM2(I,J)=HZTM1(I,J)
      ELSE
      END IF
260   CONTINUE
250   CONTINUE
      HZ(1,1)=HZ(2,1)
      HZ(1,27)=HZ(2,27)
      HZ(27,1)=HZ(27,2)
      HZ(27,27)=HZ(27,26)
      CALL WRITMS (1,HXTM2(1,1),768,K8,1)
      CALL WRITMS (1,HYTM2(1,1),768,K9,1)
      CALL WRITMS (1,HZTM2(1,1),768,K10,1)
C*******
      CALL WRITMS(1,HX(1,1),768,K4,1)
      CALL WRITMS(1,HY(1,1),768,K5,1)
      CALL WRITMS(1,HZ(1,1),768,K6,1)
C
C     SAMPLE POINTS OF INTEREST (EVEN K PLANES)
C
         IF (K.EQ.14) THEN
            WRITE (6,111) MN4,THN,HZ(10,4)
            WRITE (6,111) MN5,THN,HZ(19,4)
            WRITE (6,111) MN6,THN,HX(22,18)
         ELSE
         END IF
C
         IF (K.EQ.6) WRITE(6,111) MN1,THN,HX(18,18)
C
900   CONTINUE
      RETURN
```

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```
                  END
                  SUBROUTINE APERT
                  RETURN
                  END
                   SUBROUTINE AIRPLN
C
C ZEROES THE ELECTRIC FIELDS WITHIN THE F16 AIRCRAFT AND
C TANGENTIAL ELECTRIC FIELD COMPONENTS AT THE SURFACE
C
                  COMMON /ARRAYS/ FLD (27,27),B1 (39)
C
C       EX ZEROED
C
                  DO 1000 K=3,25
                  CALL READNS (1,FLD(1,1),768,K)
C       WING
                  IF (K.NE.3) GO TO 40
                  FLD(18,9)=0.0
                  FLD(19,9)=0.0
40                IF (K.NE.4) GO TO 50
                  DO 41 I=17,19
41                FLD(I,9)=0.0
50                IF (K.LT.5.OR.K.GT.6) GO TO 70
                  DO 51 I=16,19
51                FLD(I,9)=0.0
70                IF (K.LT.7.OR.K.GT.8) GO TO 90
                  DO 71 I=15,19
                  DO 71 J=9,10
71                FLD(I,J)=0.0
                  FLD(23,9)=0.0
                  FLD(24,9)=0.0
90                IF (K.NE.9) GO TO 100
                  DO 91 I=14,19
                  DO 91 J=9,10
91                FLD(I,J)=0.0
                  DO 92 I=22,24
92                FLD(I,9)=0.0
100               IF (K.NE.10) GO TO 110
                  DO 101 I=10,19
                  DO 101 J=9,10
101               FLD(I,J)=0.0
                  DO 102 I=21,24
102               FLD(I,9)=0.0
110               IF (K.NE.11) GO TO 120
                  DO 111 I=11,23
                  DO 111 J=9,10
111               FLD(I,J)=0.0
                  DO 112 I=11,22
112                FLD(I,8)=0.0
C       MAIN FUSELAGE
120               IF (K.LT.12.OR.K.GT.15) GO TO 126
                  DO 121 I=10,19
```

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```
        DO 121 J=5,12
121    FLD(I,J)=0.0
C
C       FORWARD FUSELAGE
C
        DO 122 I=6,9
        DO 122 J=8,10
122    FLD(I,J)=0.0
        DO 123 I=8,9
        DO 123 J=11,12
123    FLD(I,J)=0.0
        FLD(7,11)=0.0
C       REAR FUSELAGE
        DO 124 I=20,22
124    FLD(I,6)=0.0
        DO 125 I=20,23
        DO 125 J=7,12
125    FLD(I,J)=0.0
126    IF (K.NE.12.OR.K.NE.15) GO TO 130
        DO 127 I=19,20
        DO 127 J=3,4
127    FLD (I,J)=0.0
        FLD(20,5)=0.0
130    IF (K.LT.13.OR.K.GT.14) GO TO 135
        FLD(24,9)=0.0
        FLD(24,10)=0.0
C       NOSE AND COCKPIT
        DO 131 I=4,5
        DO 131 J=8,9
131    FLD(I,J)=0.0
        FLD(5,10)=0.0
        FLD(6,11)=0.0
        FLD(7,12)=0.0
        DO 132 I=8,11
        DO 132 J=13,14
132    FLD(I,J)=0.0
        FLD(12,13)=0.0
        FLD(13,13)=0.0
        FLD(9,15)=0.0
C
C       RIGHT VERTICAL STABALIZER
C
135    IF (K.NE.13) GO TO 140
        DO 136 I=19,23
        DO 136 J=13,14
136    FLD(I,J)=0.0
        FLD(17,13)=0.0
        FLD(18,13)=0.0
140    IF (K.NE.14) GO TO 160
        DO 141 I=18,23
        DO 141 J=13,14
141    FLD(I,J)=0.0
```

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```
        FLD(17,23)=0.0
        DO 142 I=20,23
        DO 142 J=15,19
142     FLD(I,J)=0.0
        FLD(20,15)=0.0
        FLD(20,16)=0.0
        DO 143 I=22,23
        DO 143 J=20,22
143     FLD(I,J)=0.0
        FLD(24,21)=0.0
        FLD(24,22)=0.0
        DO 144 I=23,24
        DO 144 J=23,24
144     FLD(I,J)=0.0
160     IF (K.NE.16) GO TO 170
        DO 161 I=11,22
        DO 161 J=8,10
161     FLD(I,J)=0.0
        FLD(23,9)=0.0
        FLD(23,10)=0.0
170     IF (K.NE.17) GO TO 180
C       WING
        DO 171 I=13,19
        DO 171 J=9,10
171     FLD(I,J)=0.0
C
C       RIGHT HORIZONTAL STABALIZER
C
        DO 172 I=21,24
172     FLD(I,9)=0.0
180     IF (K.NE.18) GO TO 190
        DO 181 I=14,19
        DO 181 J=9,10
181     FLD(I,J)=0.0
        DO 182 I=22,24
182      FLD(I,9)=0.0
190     IF (K.LT.19.OR.K.GT.20) GO TO 210
        DO 191 I=15,19
        DO 191 J=9,10
191     FLD(I,J)=0.0
        FLD(23,9)=0.0
        FLD(24,9)=0.0
210     IF (K.LT.21.OR.K.GT.22) GO TO 230
        DO 211 I=16,19
211     FLD(I,9)=0.0
230     IF (K.NE.23) GO TO 240
        DO 231 I=17,19
231     FLD(I,9)=0.0
240     IF (K.NE.24) GO TO 1000
        FLD(18,9)=0.0
        FLD(19,9)=0.0
C       STORE EX FIELDS BACK IN TO MASS STORAGE
```

```
1000  CALL WRITMS(1,FLD(1,1),'68,K,1)
C        ZERO EY
      DO 2000 K=3,24
      L=K+27
      CALL READMS (1,FLD(1,1),768,L)
      IF (K.LT.7.OR.K.GT.10) GO TO 1110
      DO 1081 I=14,19
1081      FLD(I,10)=0.0
      IF (K.NE.9) GO TO 1100
      FLD(13,10)=0.0
1100  IF (K.NE.10) GO TO 1110
      FLD(12,10)=0.0
      FLD(13,10)=0.0
1110      IF (K.NE.11) GO TO 1120
      DO 1111 I=10,22
      DO 1111 J=9,10
1111      FLD(I,J)=0.0
      FLD(23,10)=0.0
C        MAIN FUSELAGE
1120      IF (K.LT.12.OR.K.GT.15) GO TO 1130
      DO 1121 I=9,19
      DO 1121 J=6,12
1121      FLD(I,J)=0.0
C        FWD FUSELAGE
      DO 1122 I=5,8
      DO 1122 J=9,10
1122      FLD(I,J)=0.0
      DO 1123 I=7,8
      DO 1123 J=11,12
1123      FLD(I,J)=0.0
      FLD(6,11)=0.0
C        REAR FUSELAGE
      DO 1124 I=20,22
      DO 1124 J=7,12
1124      FLD(I,J)=0.0
      DO 1125 J=8,12
1125      FLD(23,J)=0.0
1130      IF (K.LT.13.OR.K.GT.14) GO TO 1126
      FLD(24,10)=0.0
1126      IF (K.NE.12.OR.K.NE.15) GO TO 1131
      DO 1127 I=18,20
      DO 1127 J=4,5
1127      FLD (I,J)=0.0
      FLD(20,6)=0.0
1131      IF (K.LT.13.OR.K.GT.14) GO TO 1135
      FLD(3,9)=0.0
      FLD(4,9)=0.0
      FLD(4,10)=0.0
      FLD(5,11)=0.0
      FLD(6,12)=0.0
      DO 1132 I=7,13
1132      FLD(I,13)=0.0
```

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```
1133        FLD(I,14)=0.0
           FLD(8,15)=0.0
           FLD(9,15)=0.0
1135        IF (K.NE.13) GO TO 1140
           DO 1136 I=16,23
1136        FLD(I,13)=0.0
           DO 1137 I=18,23
1137        FLD(I,14)=0.0
1140        IF (K.NE.14) GO TO 1160
           DO 1141 I=22,23
           DO 1141 J=13,24
1141        FLD(I,J)=0.0
           DO 1142 J=21,24
1142        FLD(24,J)=0.0
           DO 1143 J=20,22
1143        FLD(21,J)=0.0
           DO 1144 J=17,19
           DO 1144 I=20,21
1144        FLD(I,J)=0.0
           DO 1145 I=19,21
           DO 1145 J=15,16
1145        FLD(I,J)=0.0
           DO 1146 I=17,21
1146        FLD(I,14)=0.0
           DO 1147 I=16,21
1147        FLD(I,13)=0.0
1160        IF (K.NE.16) GO TO 1170
           DO 1161 I=18,22
           DO 1161 J=9,10
1161        FLD(I,J)=0.0
           FLD(23,10)=0.0
C      WING
117         IF (K.NE.17) GO TO 1180
           DO 1171 I=12,19
1171        FLD(I,10)=0.0
1180        IF (K.NE.18) GO TO 1190
           DO 1181 I=13,19
1181        FLD(I,10)=0.0
119         IF (K.LT.19.OR.K.GT.20) GO TO 2000
           DO 1191 I=14,19
1191        FLD(I,10)=0.0
C      STORE EY BACK TO MASS STORAGE
2000        CALL WRITMS(1,FLD(1,1),768,L,1)
C      EZ ZEROED
           DO 3000 K=3,24
             L=K+54
           CALL READMS(1,FLD(1,1),768,L)
C      WING TIP
           IF (K.NE.4) GO TO 2050
           DO 2041       I=17,19
2041        FLD(I,9)=0.0
2050        IF (K.NE.5) GO TO 2060
```

```
          DO 2051 I=16,19
2051          FLD(I,9)=0.0
C       PLANE
2060          IF (K.LT.6.OR.K.GT.7) GO TO 2080
          DO 2061 I=15,19
2061          FLD(I,9)=0.0
C       WING
2080          IF (K.NE.8) GO TO 2090
          DO 2081 J=9,10
          DO 2081 I=14,19
20(1          FLD(I,J)=0.0
C
C       RIGHT HAND STABALIZER
C
          DO 2082 I=22,24
2082          FLD(I,9)=0.0
2090          IF (K.NE.9) GO TO 2100
          DO 2091 I=14,19
          DO 2091 J=9,10
2091          FLD(I,J)=0.0
          DO 2092 I=22,24
2092          FLD(I,9)=0.0
2100          IF (K.NE.10) GO TO 2110
          DO 2101 I=13,19
          DO 2101 J=9,10
2101          FLD(I,J)=0.0
          DO 2102 I=21,24
2102          FLD(I,9)=0.0
2110          IF (K.NE.11) GO TO 2120
          DO 2111 I=12,24
2111          FLD(I,9)=0.0
          DO 2112 I=12,19
2112      FLD(I,10)=0.0
2120          IF (K.NE.12) GO TO 2130
          DO 2121 I=10,22
          DO 2121 J=8,10
2121          FLD(I,J)=0.0
          FLD(23,9)=0.0
          FLD(23,10)=0.0
2130          IF (K.LT.13.OR.K.GT.15) GO TO 2140
          DO 2131 I=9,19
          DO 2131 J=5,12
2131          FLD(I,J)=0.0
          DO 2132 I=5,8
          DO 2132 J=8,10
2132          FLD(I,J)=0.0
          DO 2133 I=7,8
          DO 2133 J=11,12
2133          FLD(I,J)=0.0
          FLD(6,11)=0.0
          DO 2134 I=20,22
          DO 2134 J=6,12
```

```
2134        FLD(I,J)=0.0
        DO 2135 J=7,12
2135        FLD(23,J)=0.0
2140        IF (K.NE.14) GO TO 2160
        FLD(24,9)=0.0
        FLD(24,10)=0.0
        DO 2141 I=3,4
        DO 2141 J=8,9
2141        FLD(I,J)=0.0
        FLD(4,10)=0.0
        FLD(5,11)=0.0
        FLD(6,12)=0.0
        DO 2142 I=7,11
        DO 2142 J=13,14
2142        FLD(I,J)=0.0
        FLD(12,13)=0.0
        FLD(13,13)=0.0
        FLD(8,15)=0.0
        FLD(9,15)=0.0
        DO 2143 I=16,23
2143        FLD(I,13)=0.0
        DO 2144 I=18,23
2144        FLD(I,14)=0.0
2160        IF (K.NE.16) GO TO 2170
        DO 2161 I=10,22
        DO 2161 J=8,10
2161        FLD(I,J)=0.0
        FLD(23,9)=0.0
        FLD(23,10)=0.0
2170        IF (K.NE.17) GO TO 2180
        DO 2171 I=12,24
2171        FLD(I,9)=0.0
        DO 2172 I=12,19
2172        FLD(I,10)=0.0
2180        IF (K.NE.18) GO TO 2190
        DO 2181 I=13,19
        DO 2181 J=9,10
2181        FLD(I,J)=0.0
        DO 2182 I=21,24
2182        FLD(I,9)=0.0
2190        IF (K.LT.19.OR.K.GT.20) GO TO 2210
        DO 2191 I=14,19
        DO 2191 J=9,10
2191        FLD(I,J)=0.0
        DO 2192 I=22,24
2192        FLD(I,9)=0.0
2210        IF (K.LT.21.OR.K.GT.22) GO TO 2230
        DO 2211 I=15,19
2211        FLD(I,9)=0.0
2230        IF(K.NE.23) GO TO 2240
        DC 2231 I=16,19
2231        FLD(I,9)=0.0
```

119

```
2240      IF (K.NE.24) GO TO 3000
          DO 2241 I=17,19
2241         FLD(I,9)=0.0
C
C         STORE EZ BACK TO MASS STORAGE
C
3000         CALL WRITMS (1,FLD(1,1),768,L,1)
          RETURN
          END
END OF FILE
```

Appendix C

Sensor Plots

This appendix contains graphs of the ten sensors for both the radiation and absorption boundary conditions. Each page contains one graph for the absorption boundary conditions and one graph for the radiation boundary condition. Each graph is made up of 1000 data points calculated from the corresponding programs in Appendix A or B. The points were connected with a natural cubic spline. The only differences in the two codes are the boundary conditions as annotated in the program. Both plots on the same page are for identical time periods so that side-by-side comparisons could be made. The programs were run for results out to 2.5 microseconds. The graphs in this appendix only reflect the first 1.0 microseconds. The graphs beyond 1.0 microseconds were only continuations of the same trends as previous graphs, so they were deleted for brevity. Also, Absorption and Radiation Boundary Conditions are abbreviated ABC and RBC respectively on the plots.
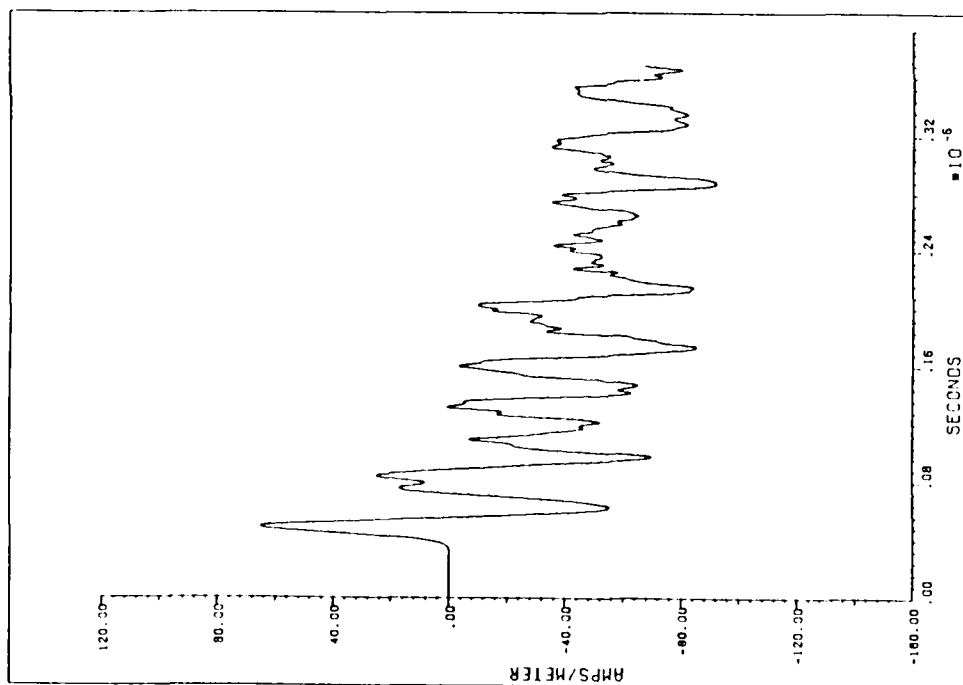
(a) ABC
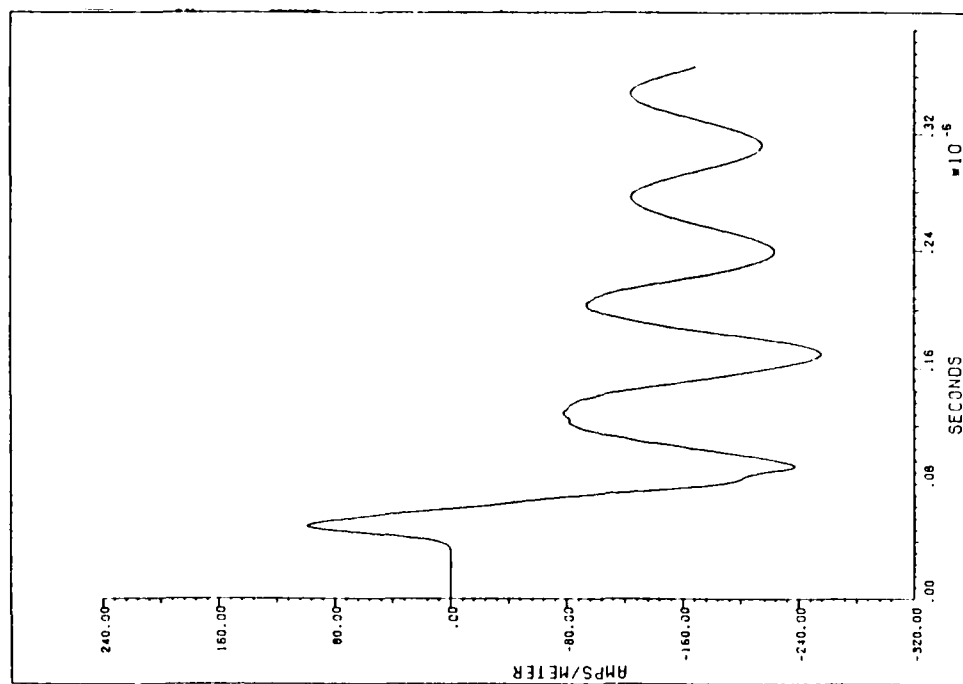
(b) RBC

Figure 27. Sensor One, H-field, Right Wing, $H_x(18,10,6)$

122
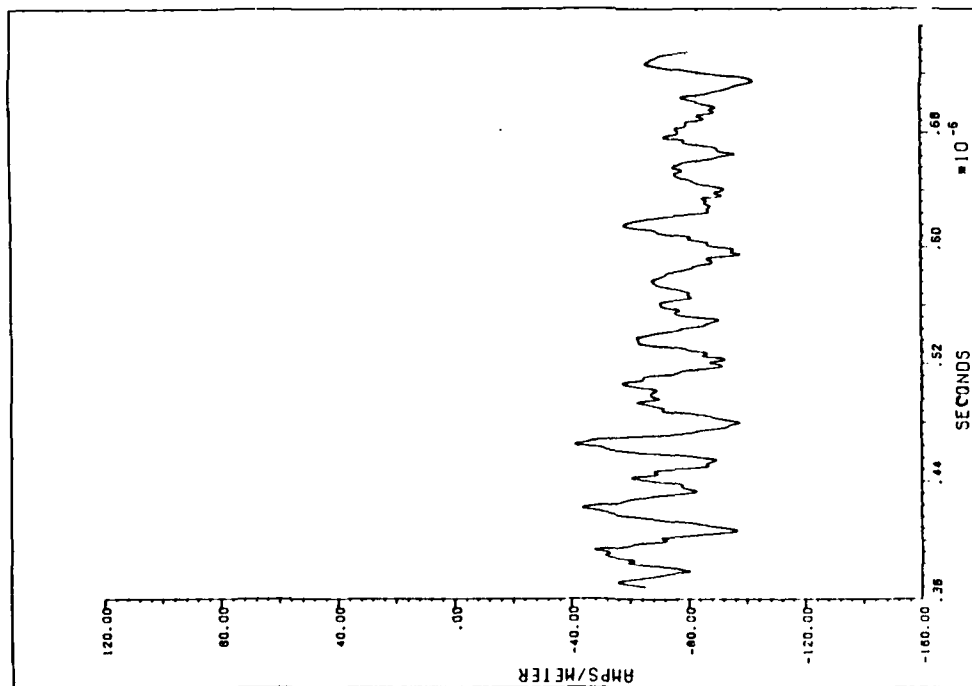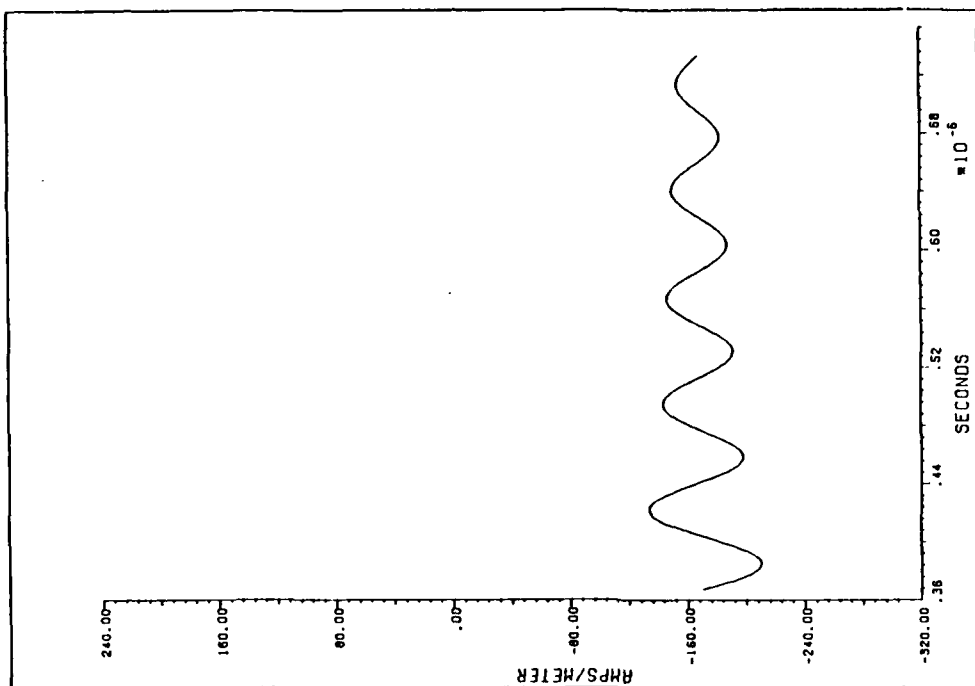
(a) ABC

(b) RBC

Figure 28. Sensor One, H-field, Right Wing, $H_x(18,10,6)$

123
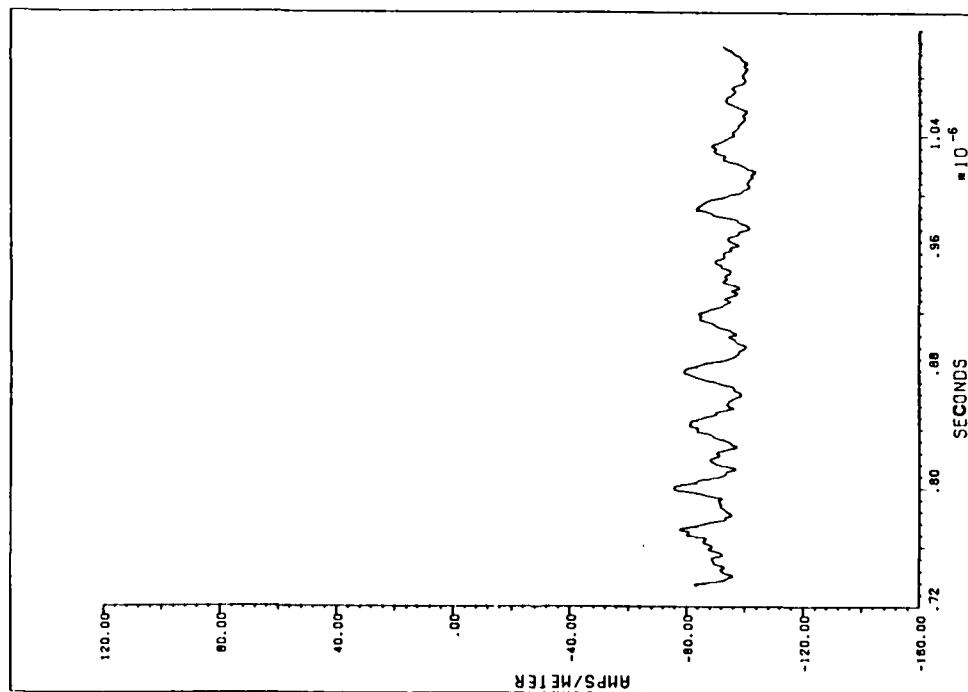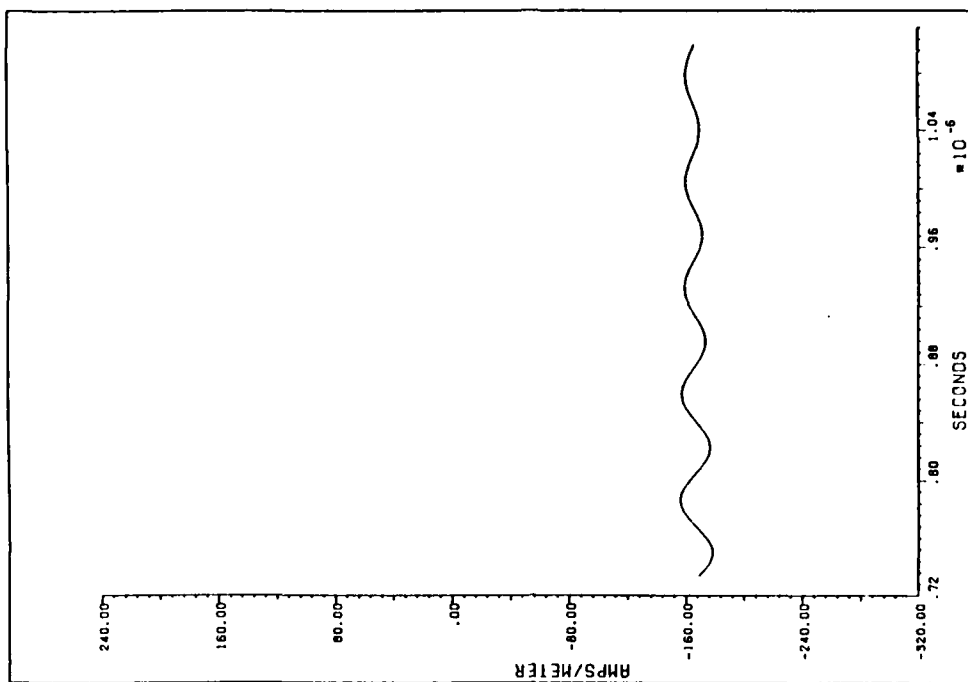
(a) ABC

(b) RBC

Figure 29. Sensor One, H-field, Right Wing, $H_x(18,10,6)$

124
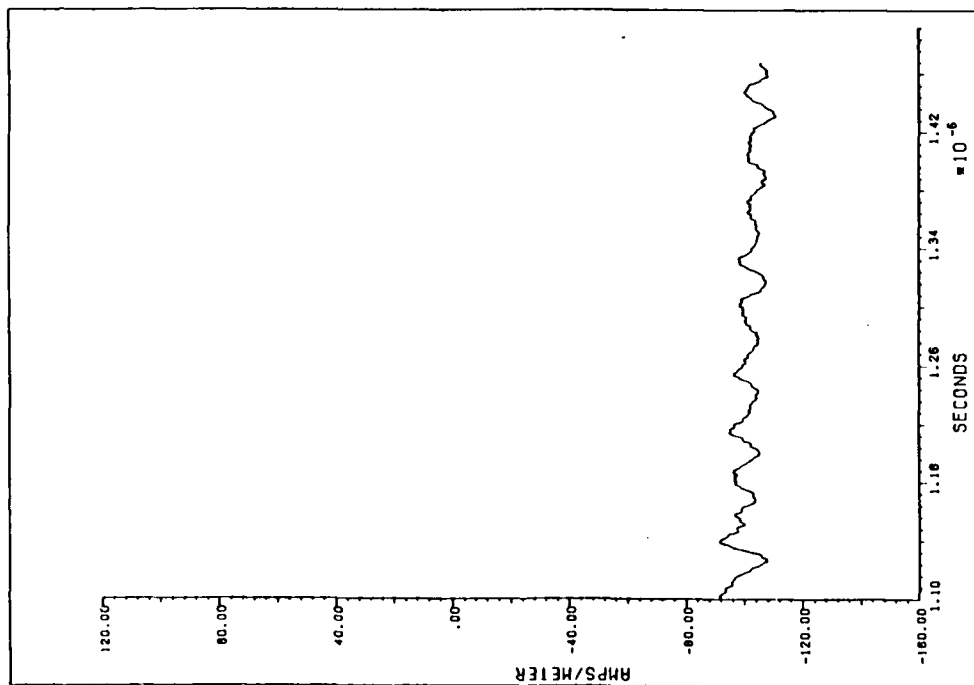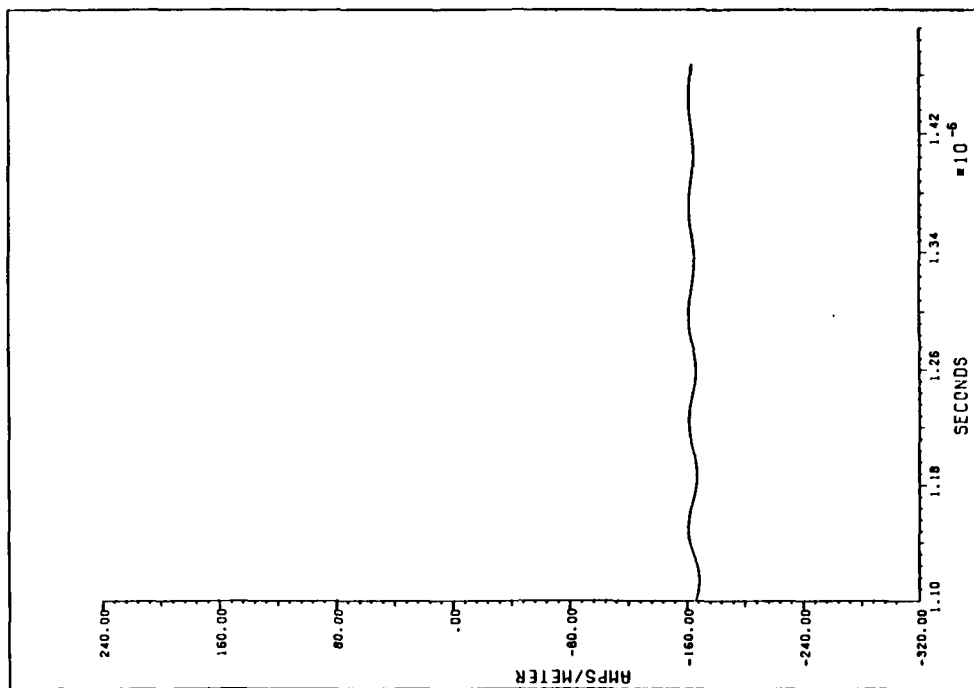
(a) ABC　　　(b) RBC

Figure 30.　Sensor One, H-field, Right Wing, $H_x(18,10,6)$

125
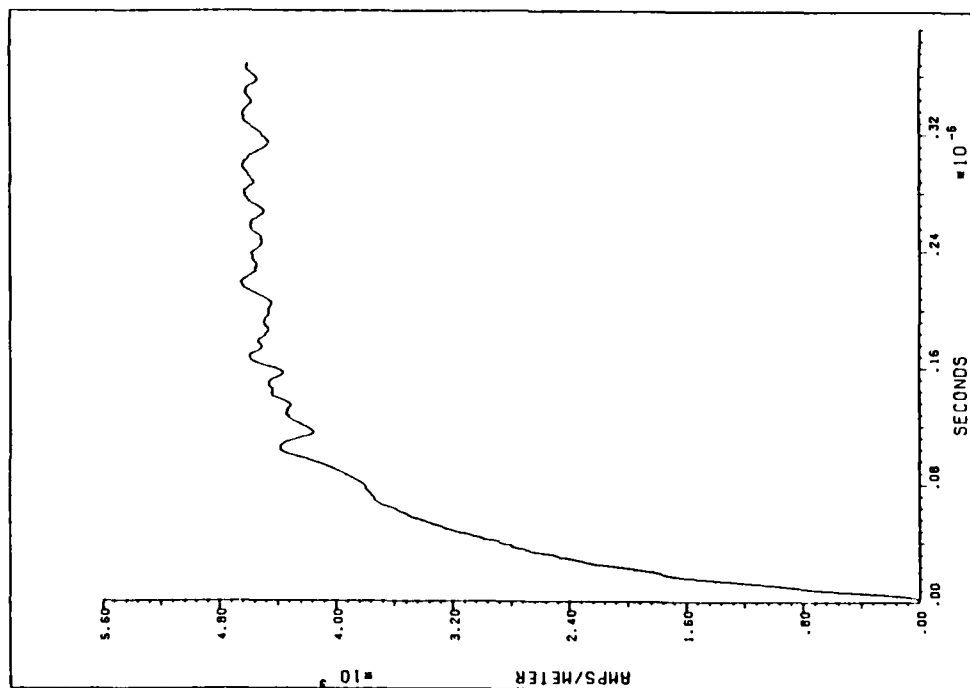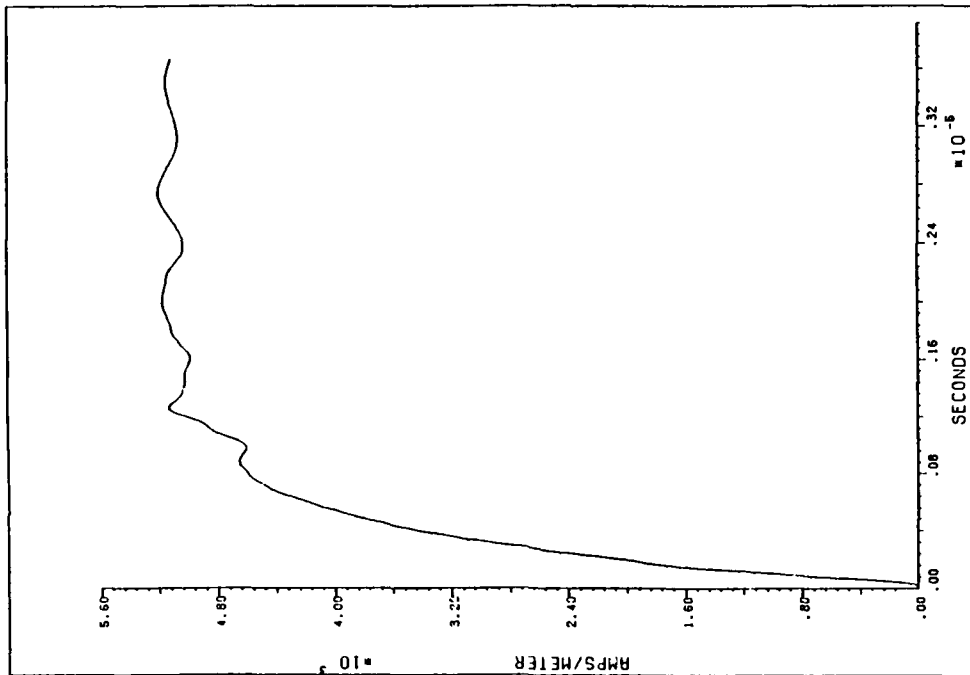
(a) ABC

(b) RBC

Figure 31. Sensor Two, H-field, Nose, $H_z(4,10,13)$

126
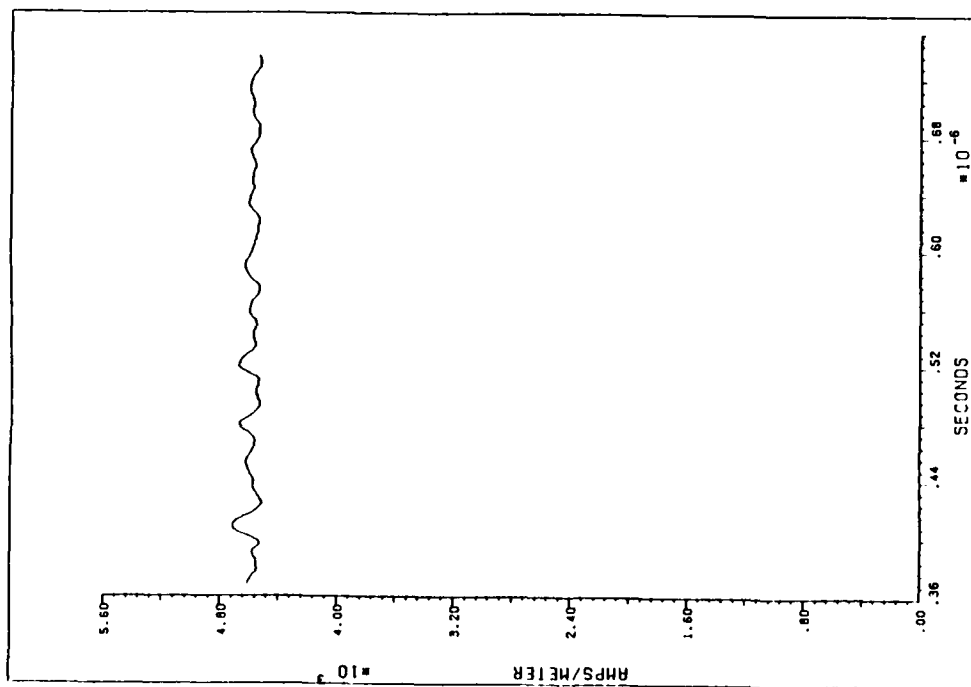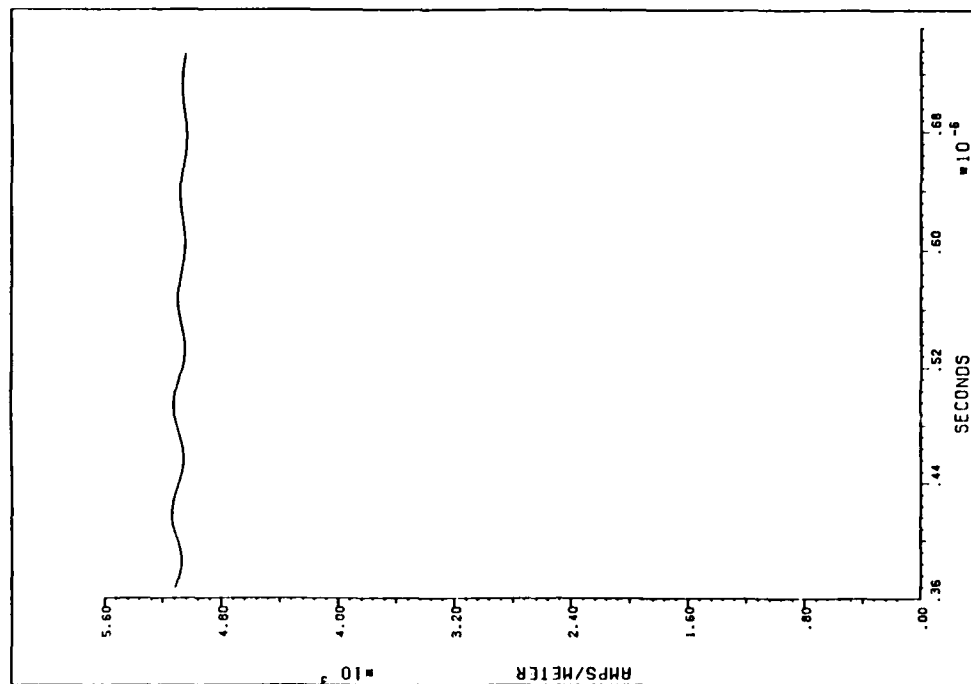
(a) ABC

(b) RBC

Figure 32. Sensor Two, H-field, Nose, $H_z(4,10,13)$

127
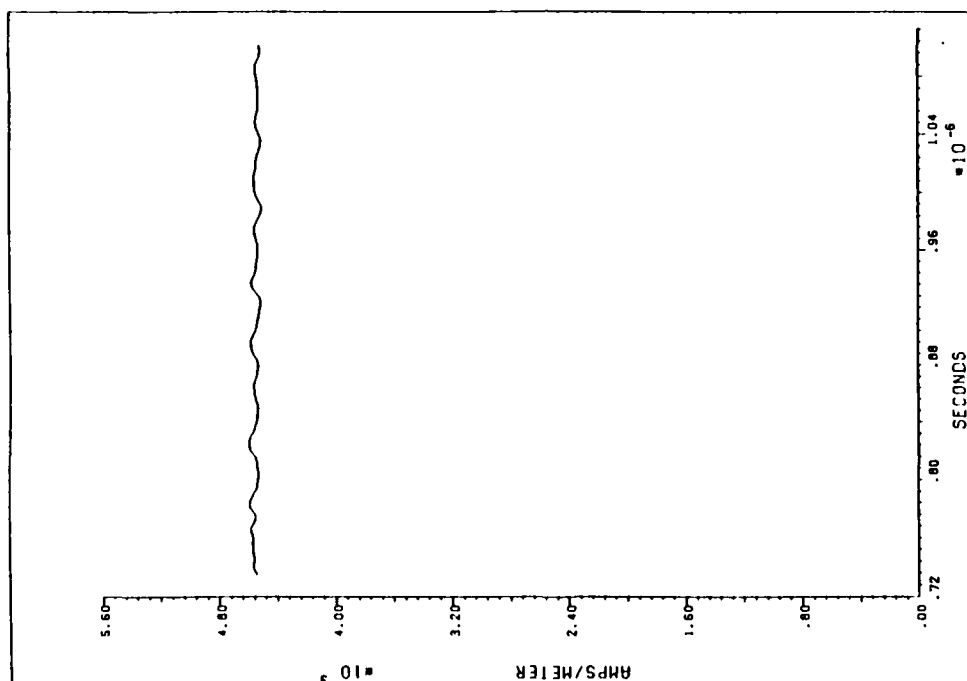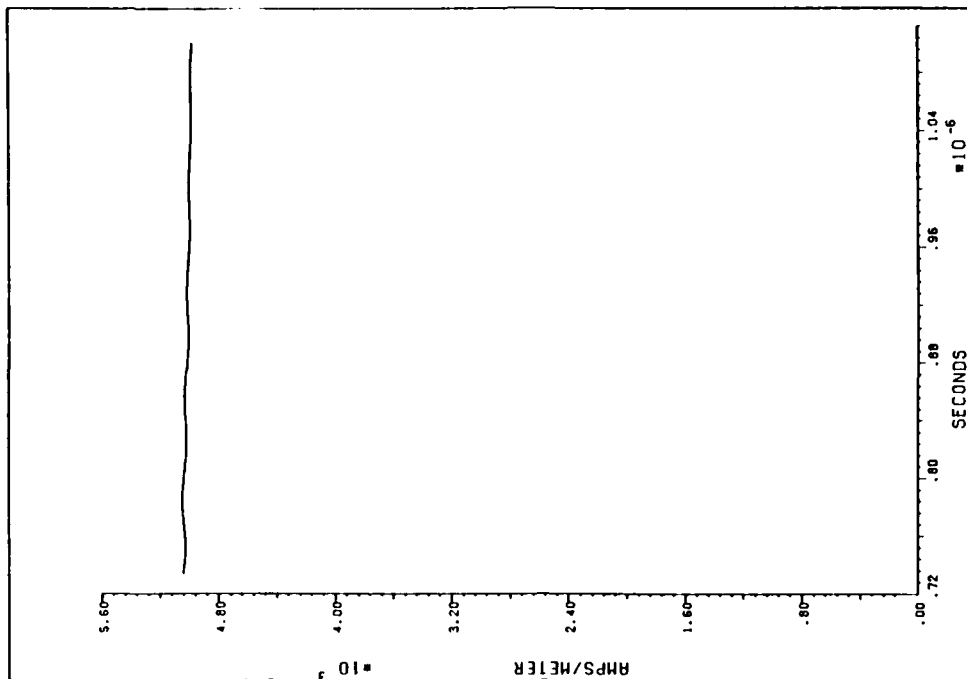
(a) ABC

(b) RBC

Figure 33. Sensor Two, H-field, Nose, $H_z(4,10,13)$

128
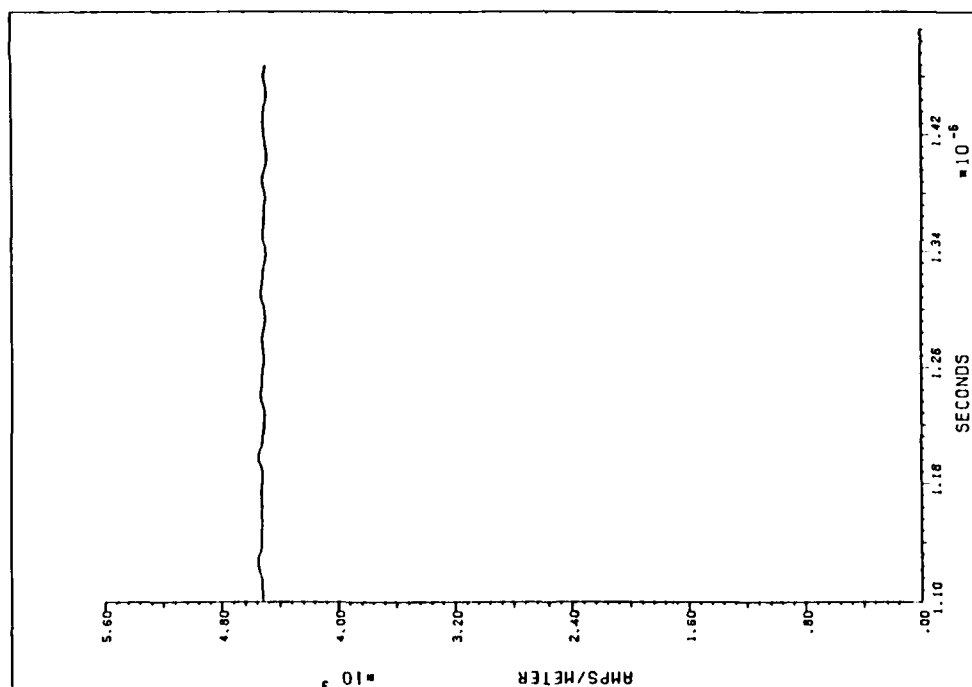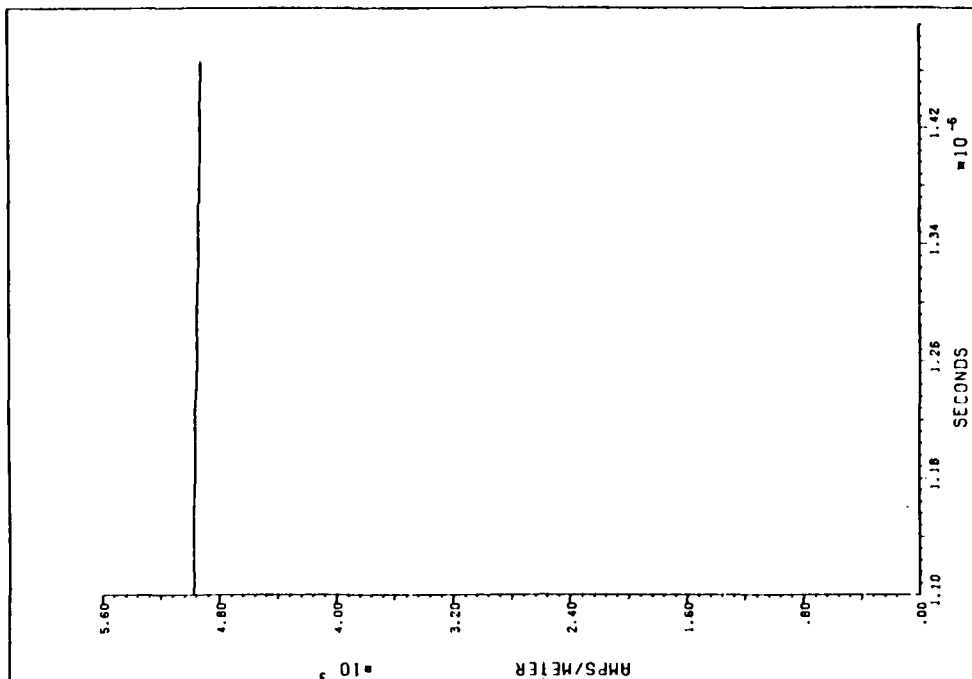
(a) ABC   (b) RBC

Figure 34.   Sensor Two, H-field, Nose, $H_z(4,10,13)$

129
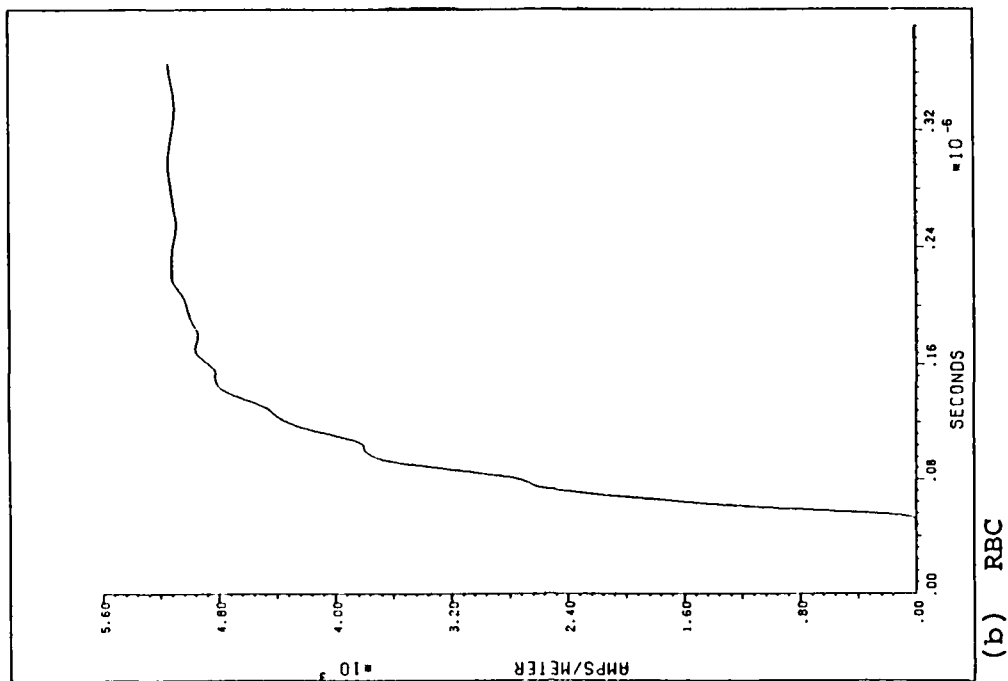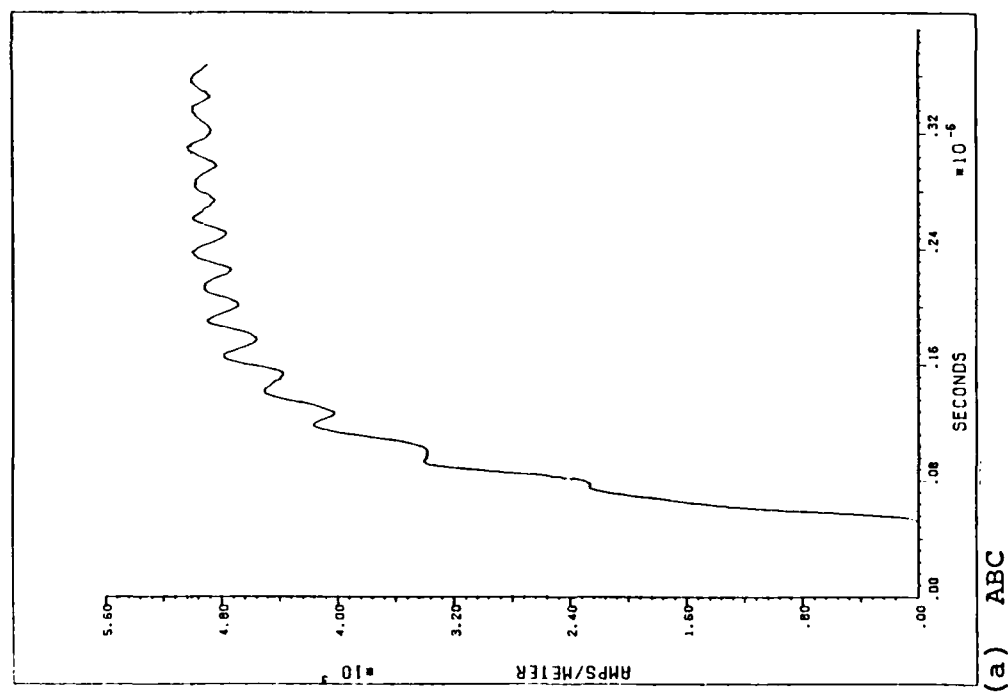
(a) ABC (b) RBC

Figure 35. Sensor Three, H-field, Engine Burner Can, $H_z(24,11,13)$
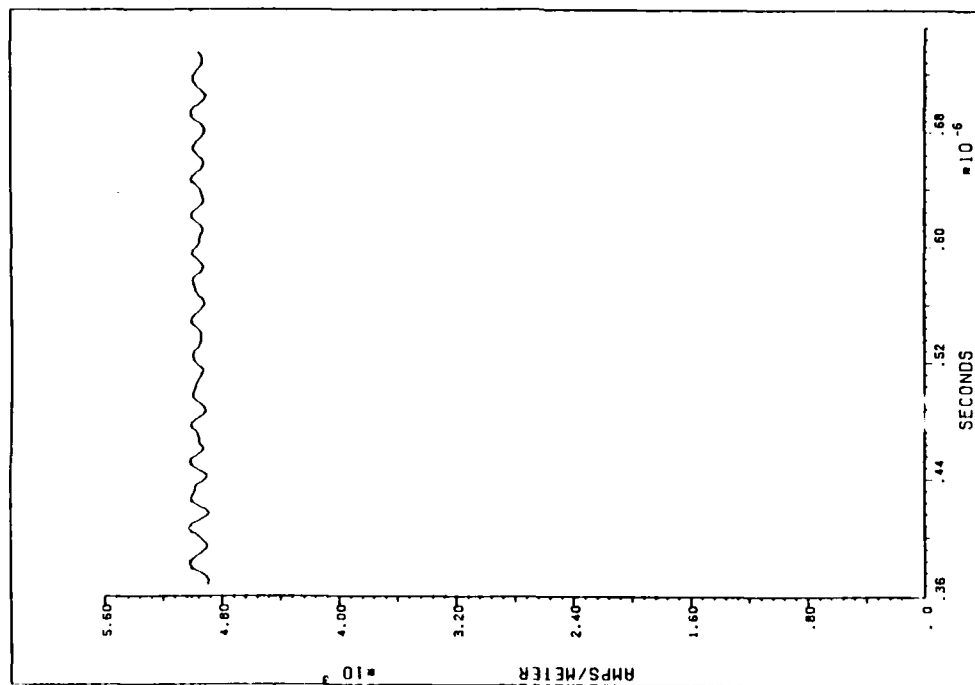
(a) ABC
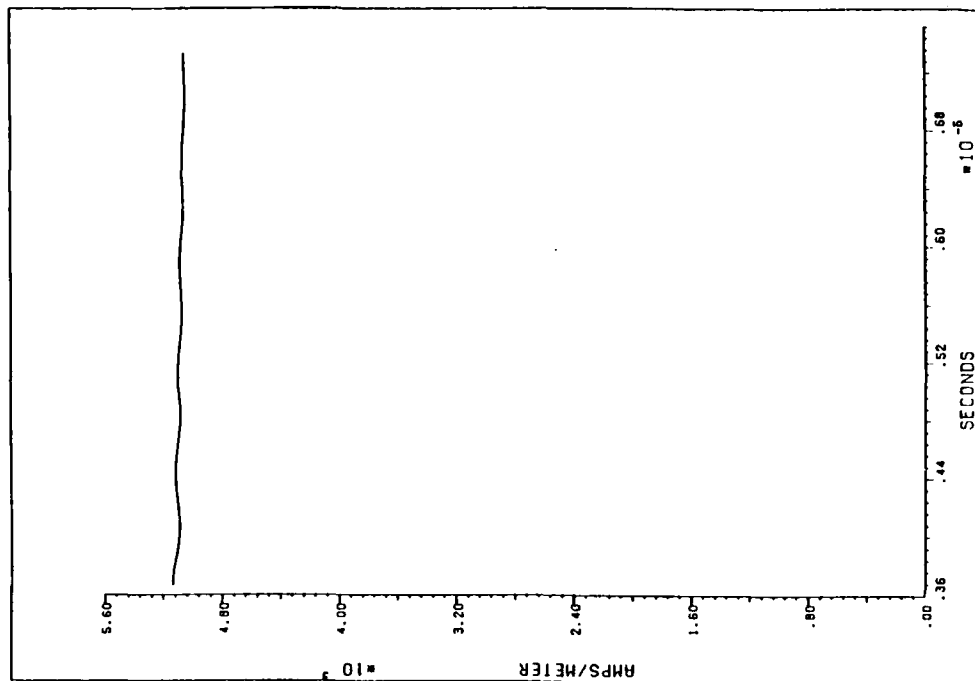
(b) RBC

Figure 36. Sensor Three, H-field, Engine Burner Can, $H_z(24,11,13)$

131
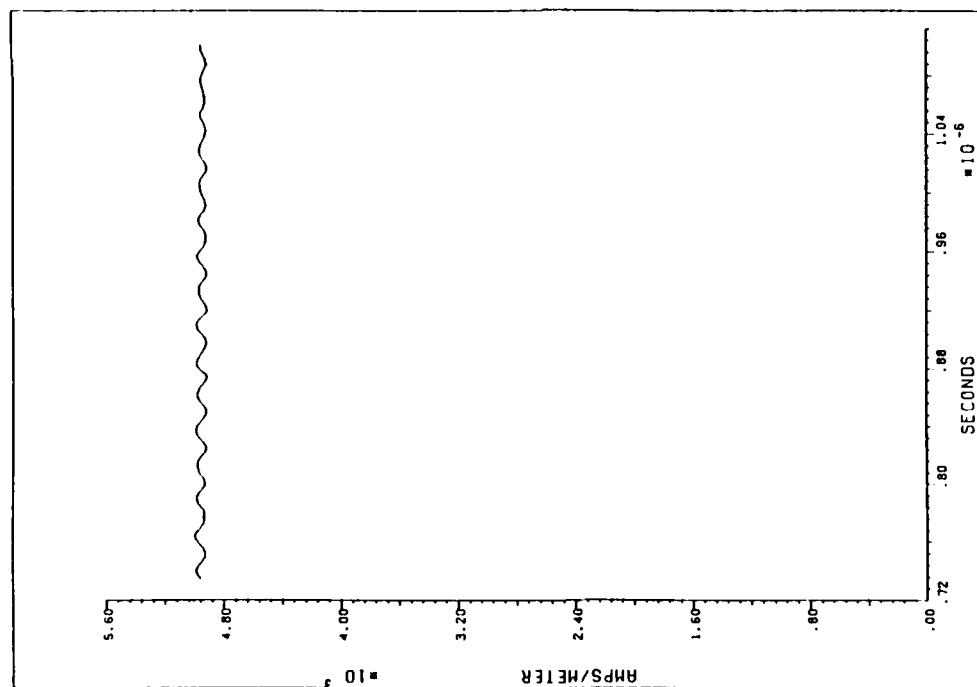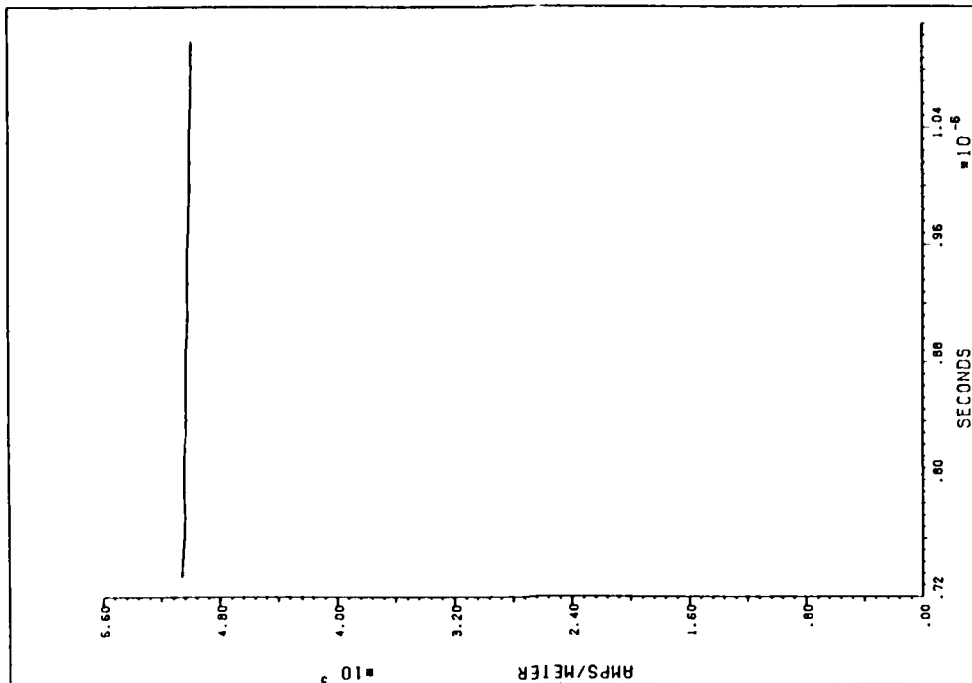
(a) ABC

(b) RBC

Figure 37. Sensor Three, H-field, Engine Burner Can, $H_z(24,11,13)$

132
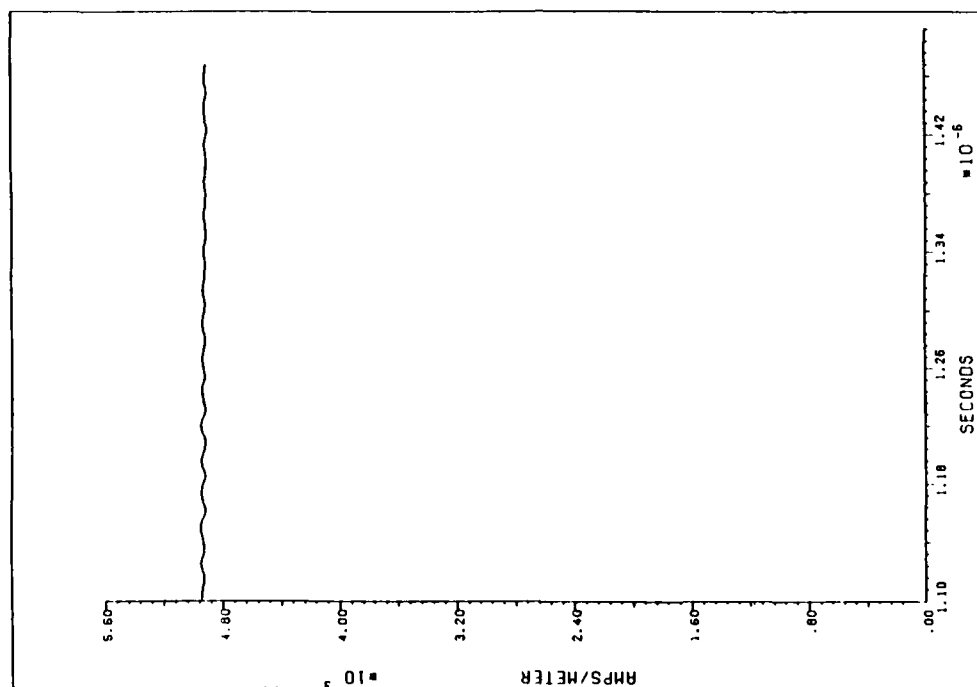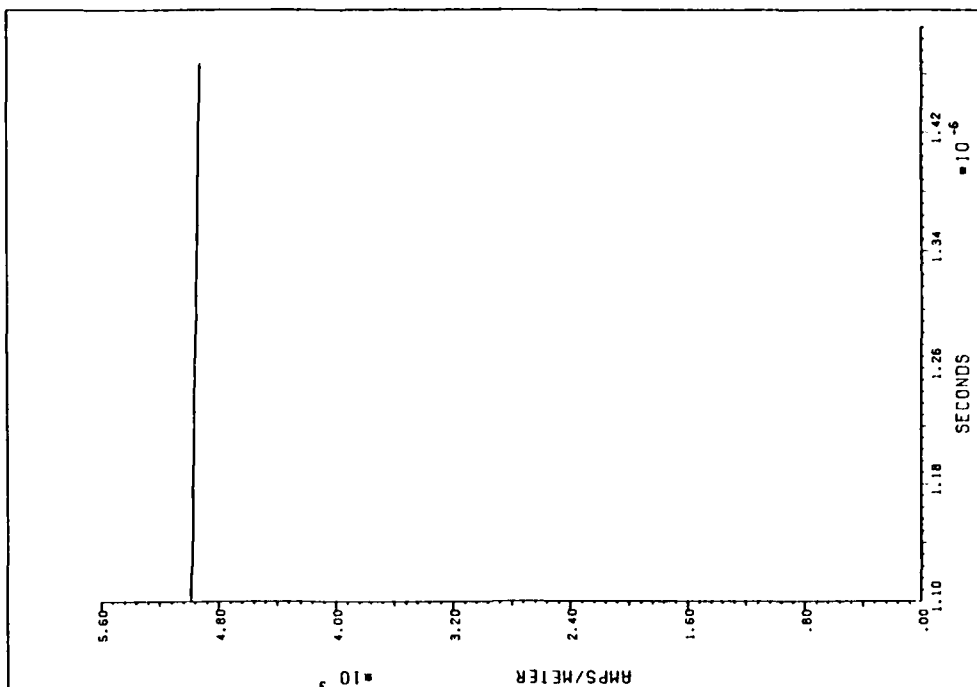
(a) ABC

(b) RBC

Figure 38. Sensor Three, H-field, Engine Burner Can, $H_z(24,11,13)$

133
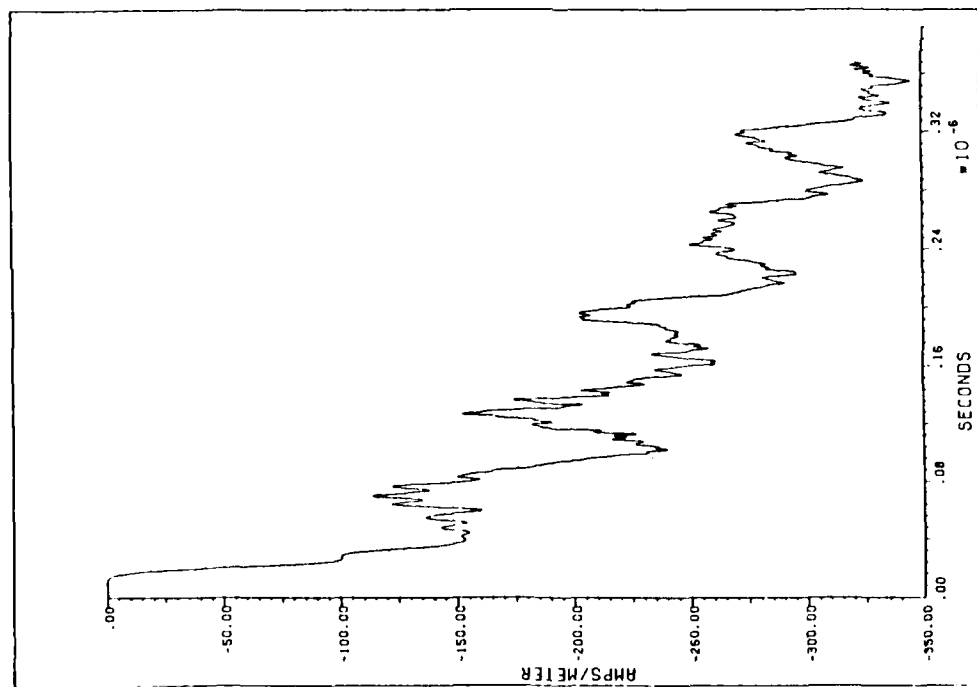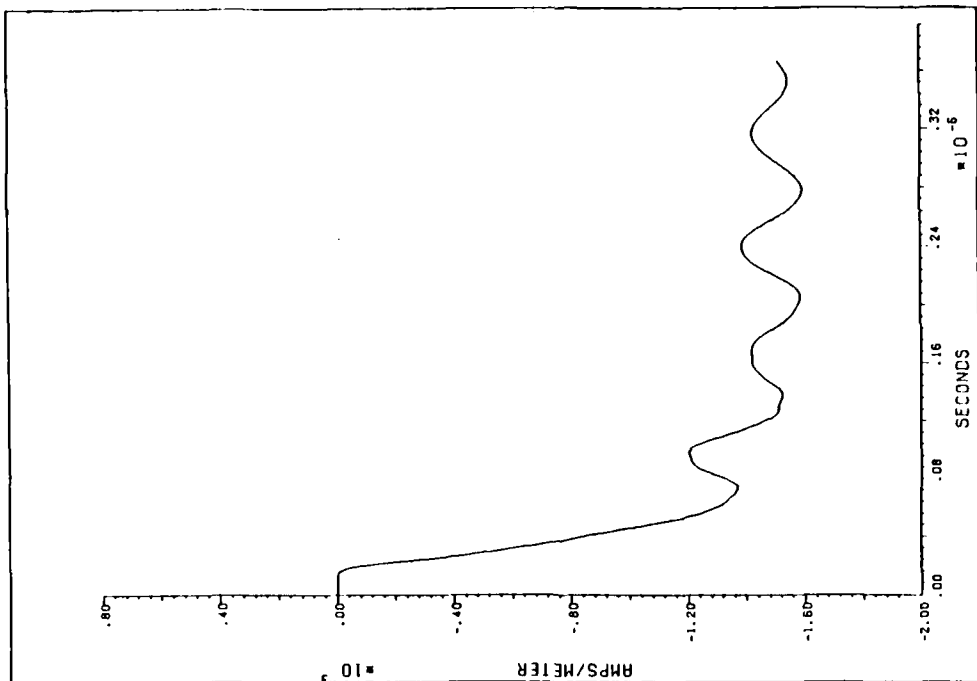
Figure 39. Sensor Four, H-field, Forward Fuselage Bottom, $H_z(10,4,14)$

(a) ABC

(b) RBC

134
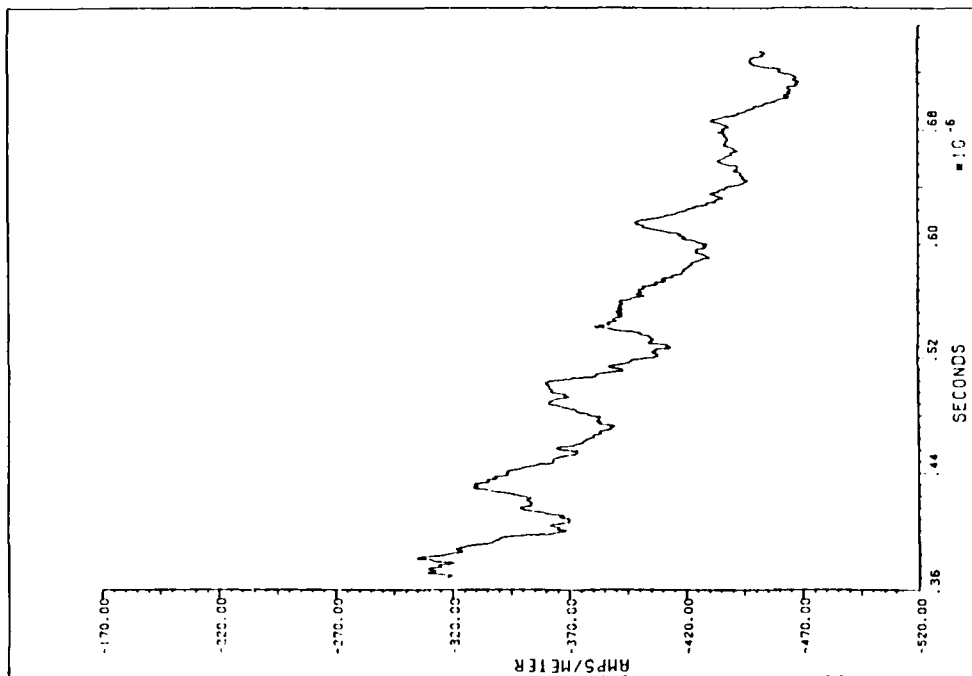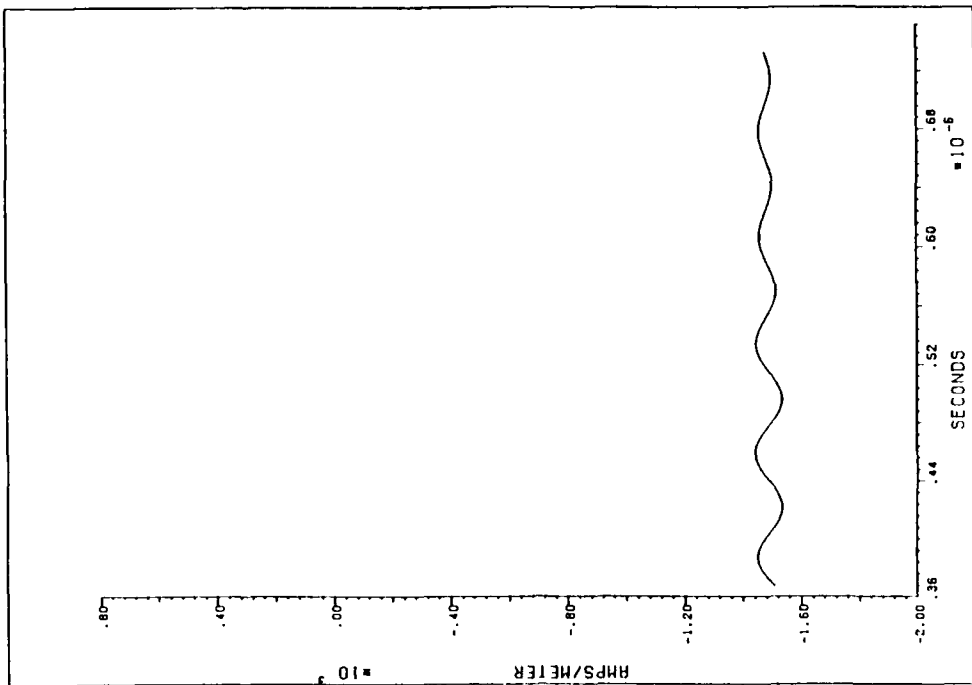
(b) RBC

(a) ABC

Figure 40. Sensor Four, H-field, Forward Fuselage Bottom, $H_z(10,4,14)$

135
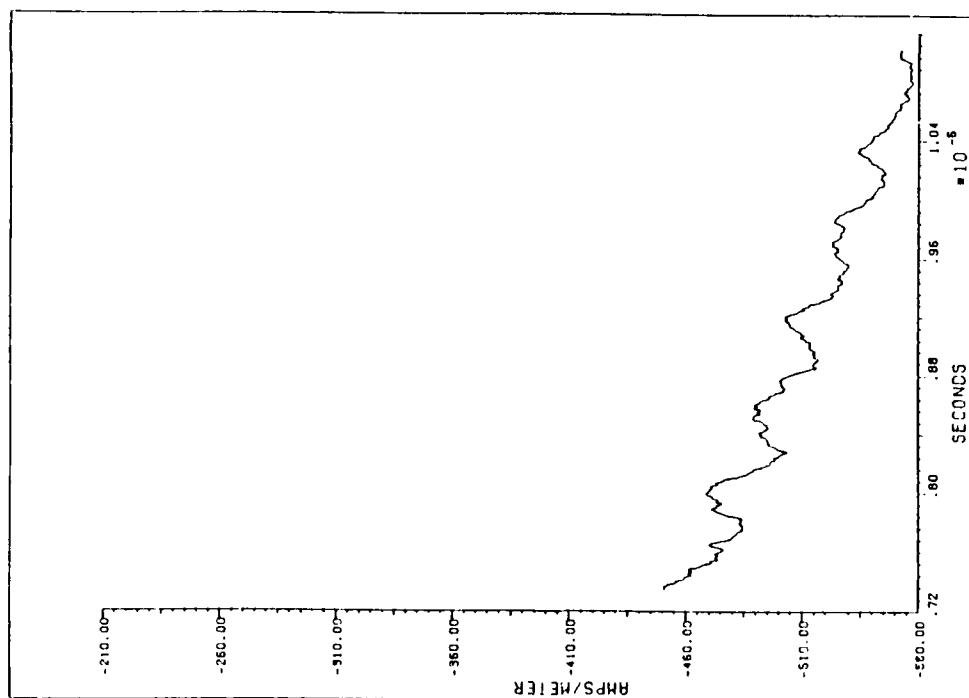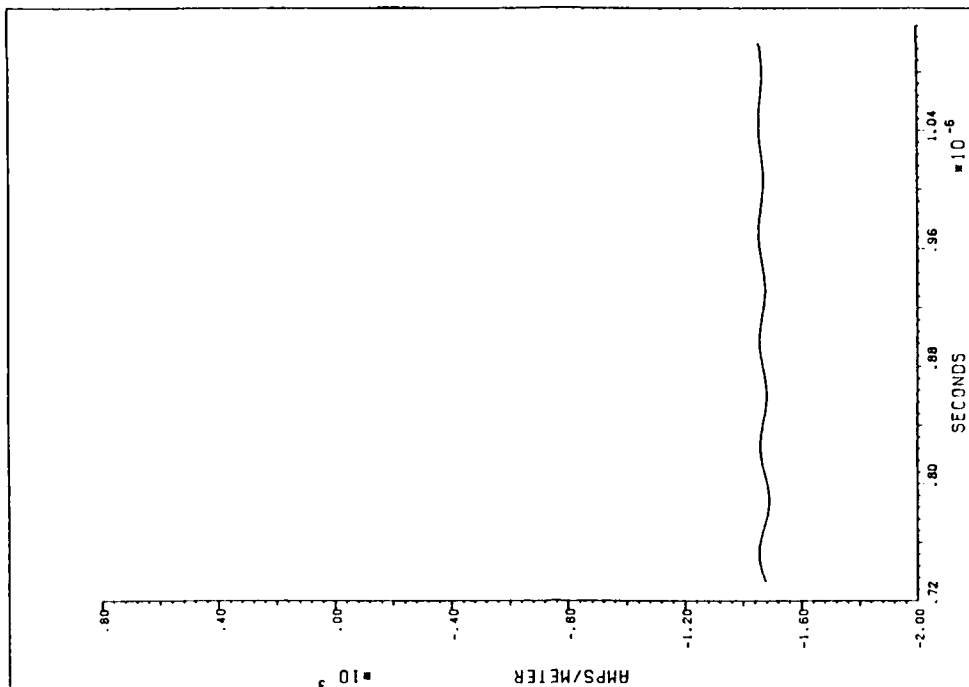
(a) ABC

(b) RBC

Figure 41. Sensor Four, H-field, Forward Fuselage Bottom, $H_z(10,4,14)$

136
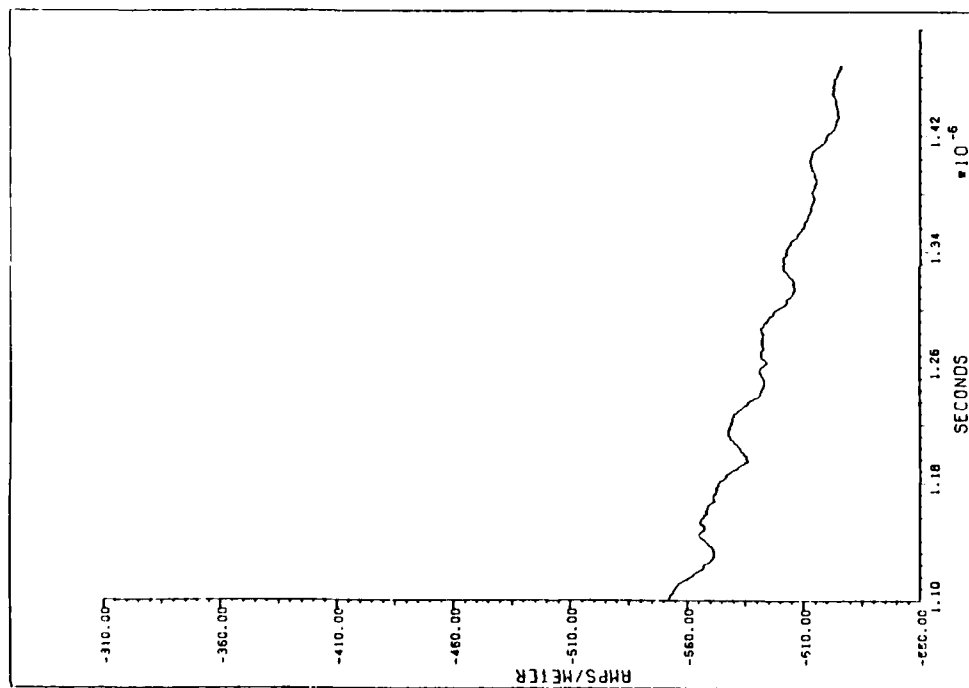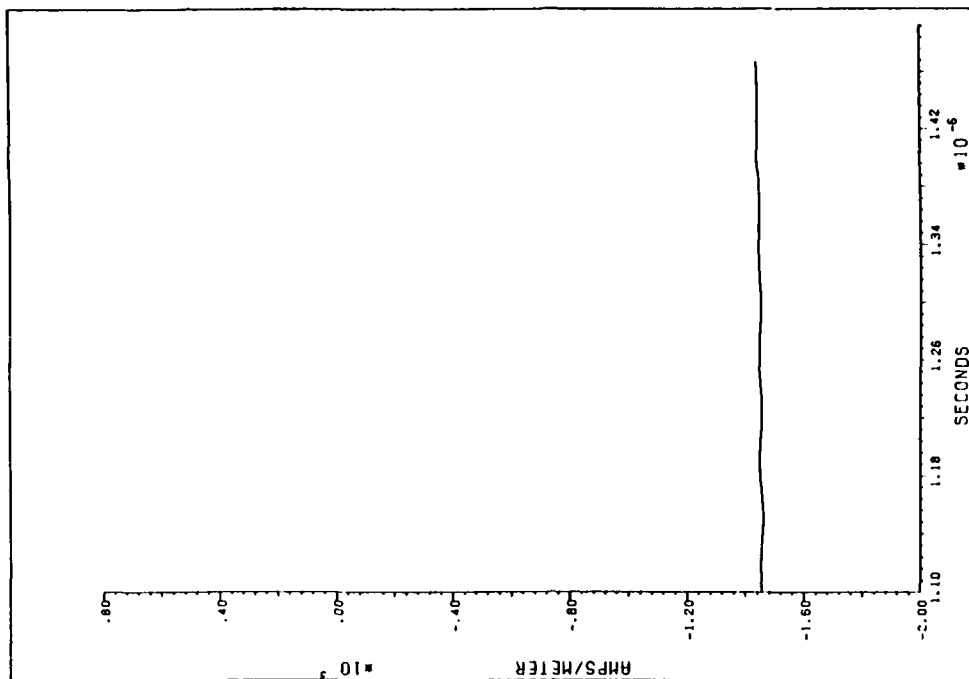
(b) RBC

(a) ABC

Figure 42. Sensor Four, H-field, Forward Fuselage Bottom, $H_z(10,4,14)$

137
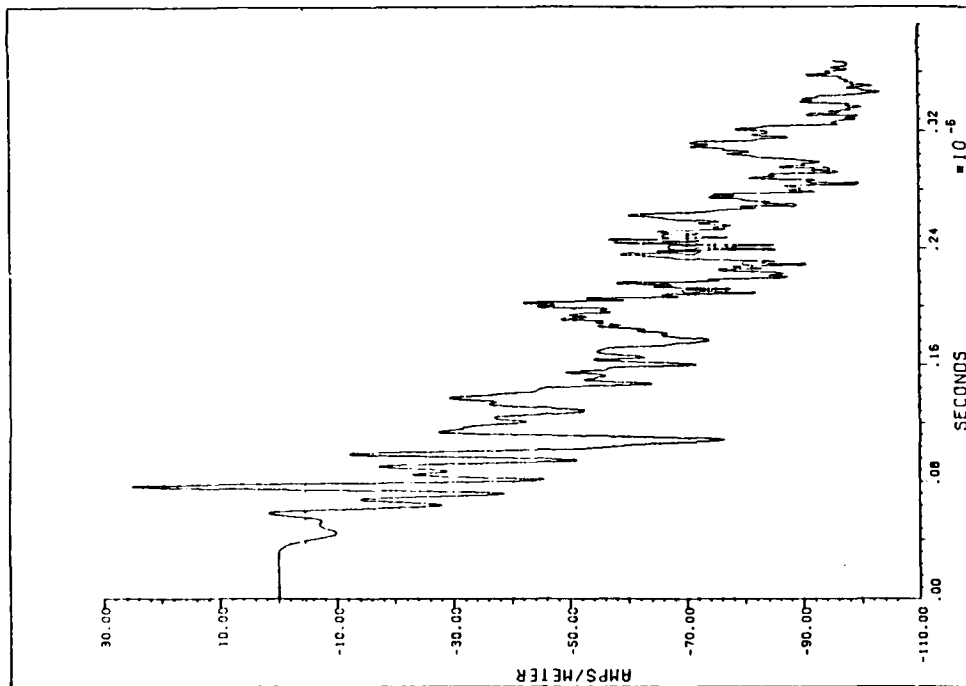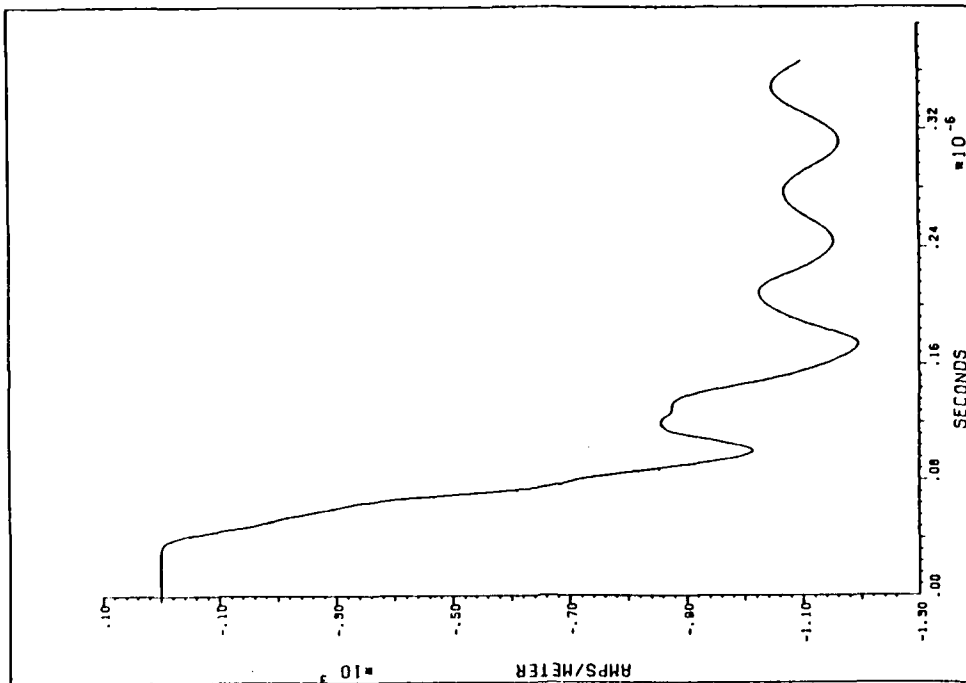
(a) ABC

(b) RBC

Figure 43. Sensor Five, H-field, Rear Fuselage Bottom, $H_z(19,4,14)$

138
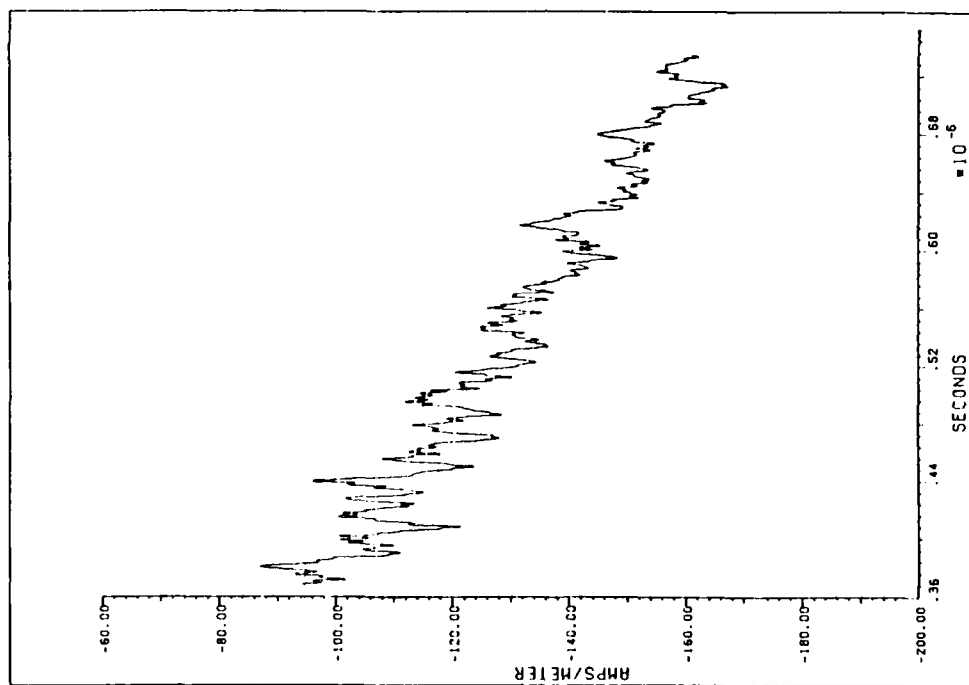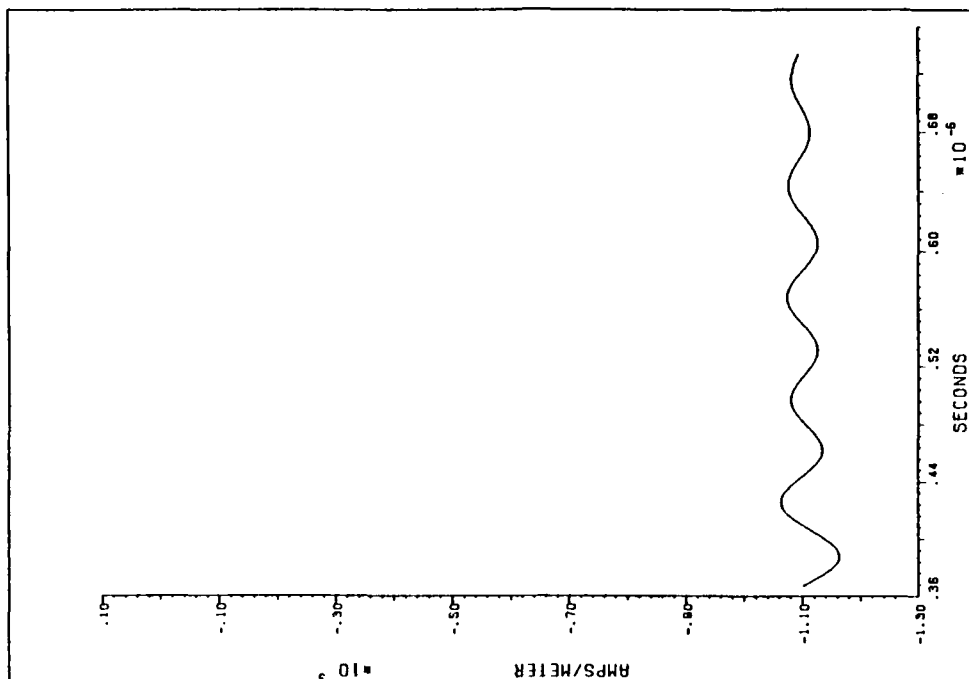
(a) ABC

(b) RBC

Figure 44. Sensor Five, H-field, Rear Fuselage Bottom, $H_z(19,4,14)$
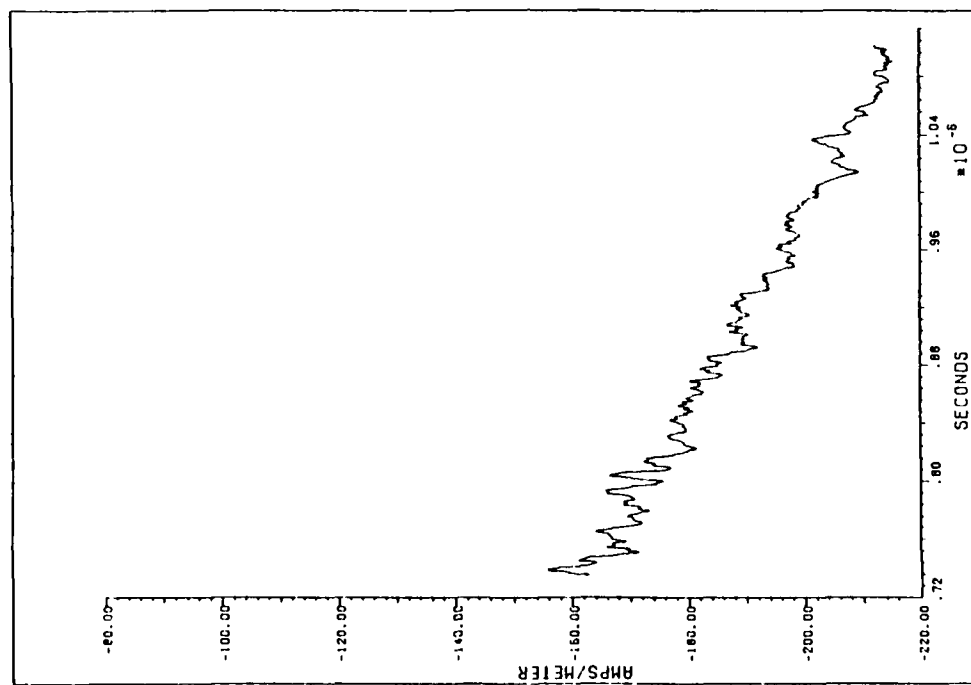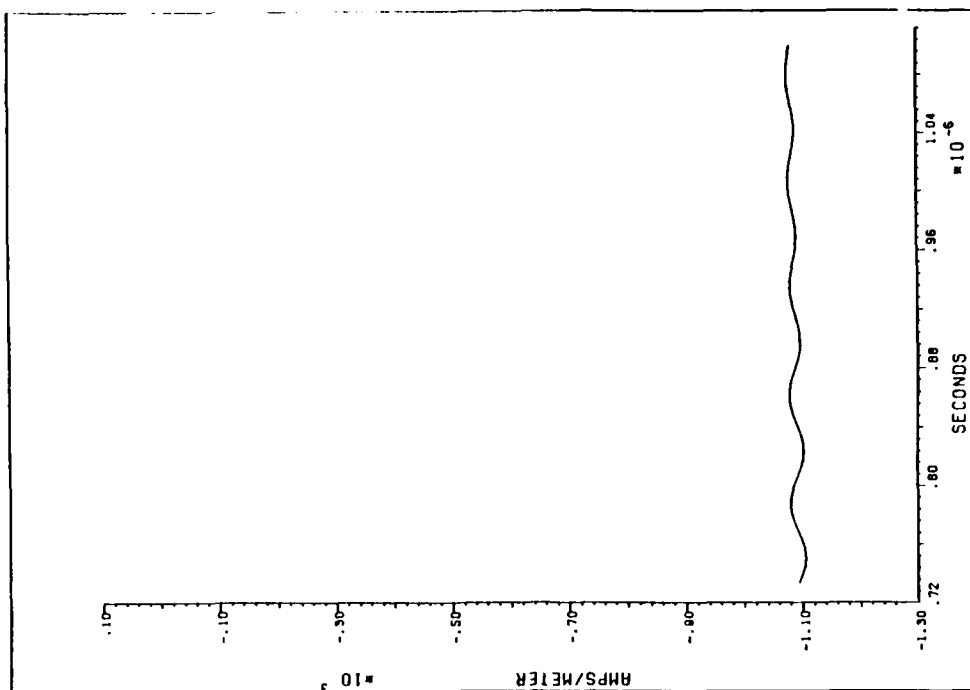
(a) ABC

(b) RBC

Figure 45. Sensor Five, H-field, Rear Fuselage Bottom, $H_z(19,4,14)$
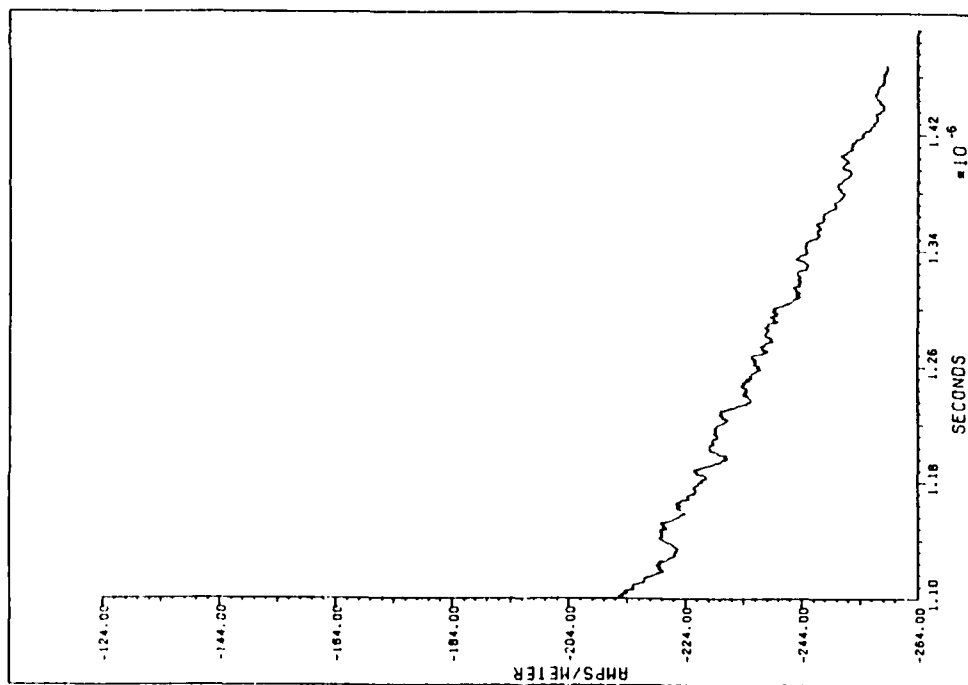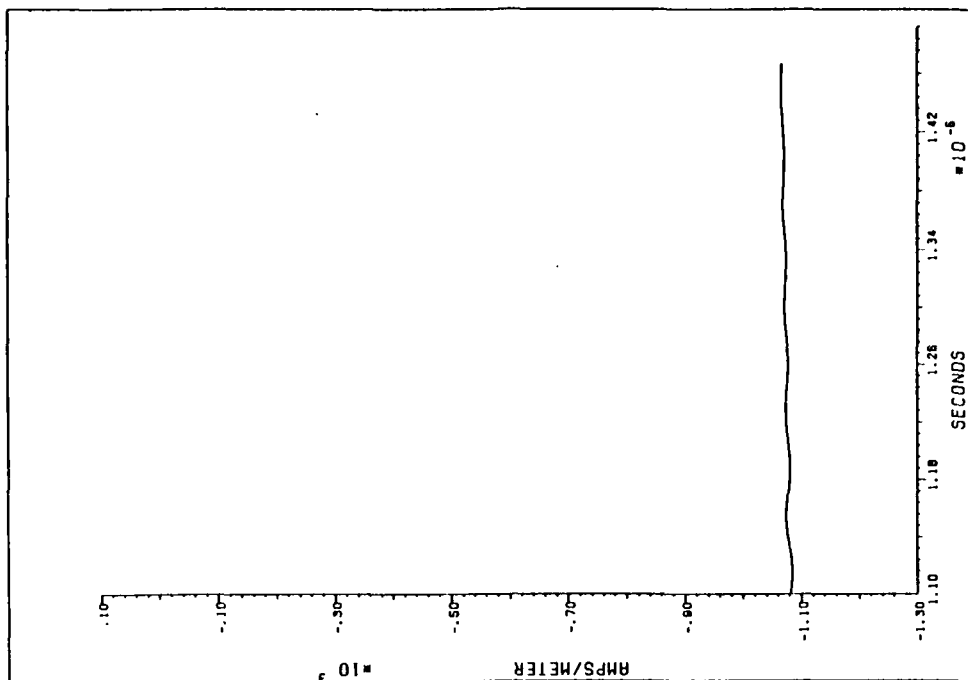
(a) ABC   (b) RBC

Figure 46. Sensor Five, H-field, Rear Fuselage Bottom, $H_z(19,4,14)$

141
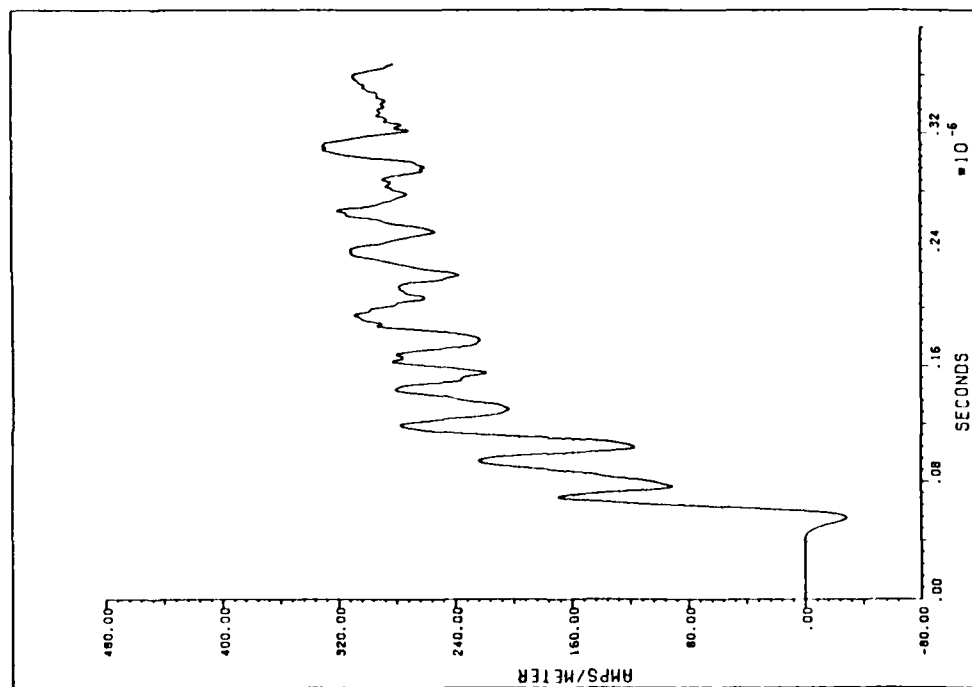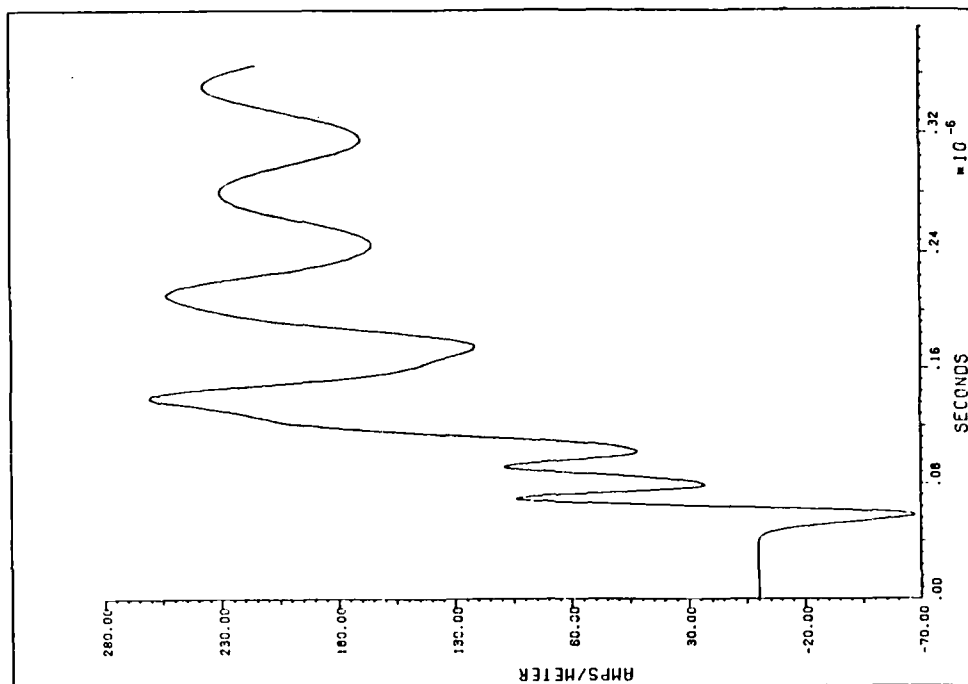
(a) ABC (b) RBC

Figure 47. Sensor Six, H-field, Vertical Stabilizer, $H_x(22,18,14)$

142
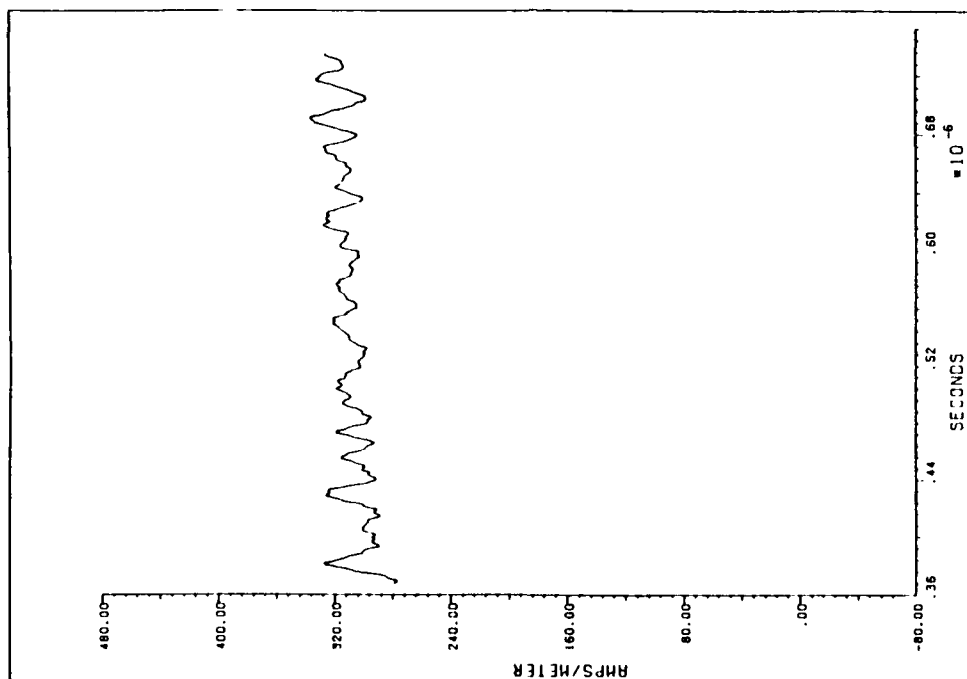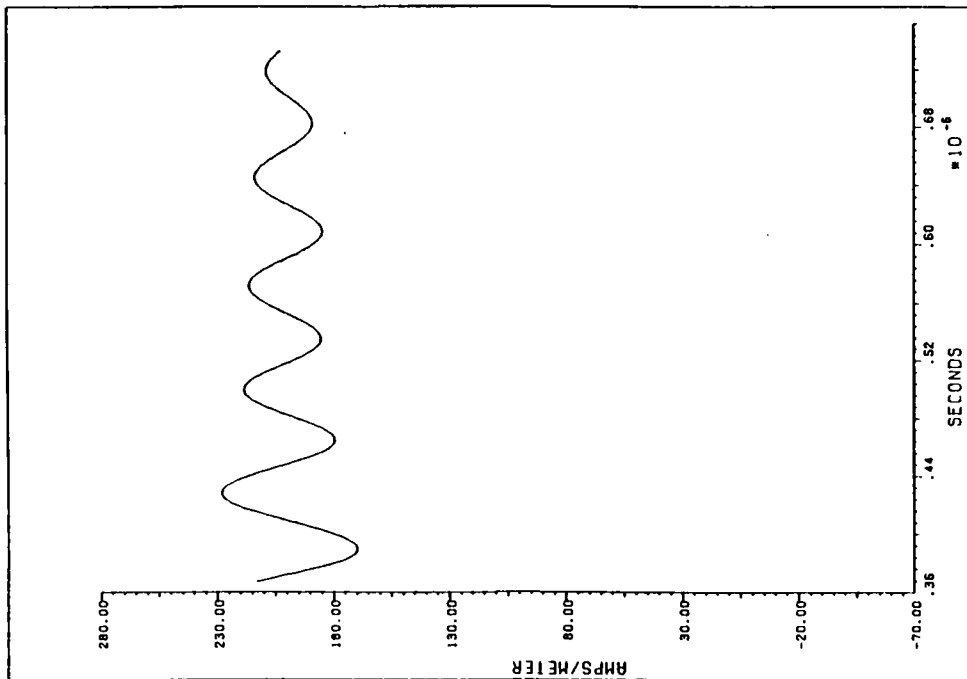
(a) ABC

(b) RBC

Figure 48. Sensor Six, H-field, Vertical Stabilizer, $H_x(22,18,14)$

143
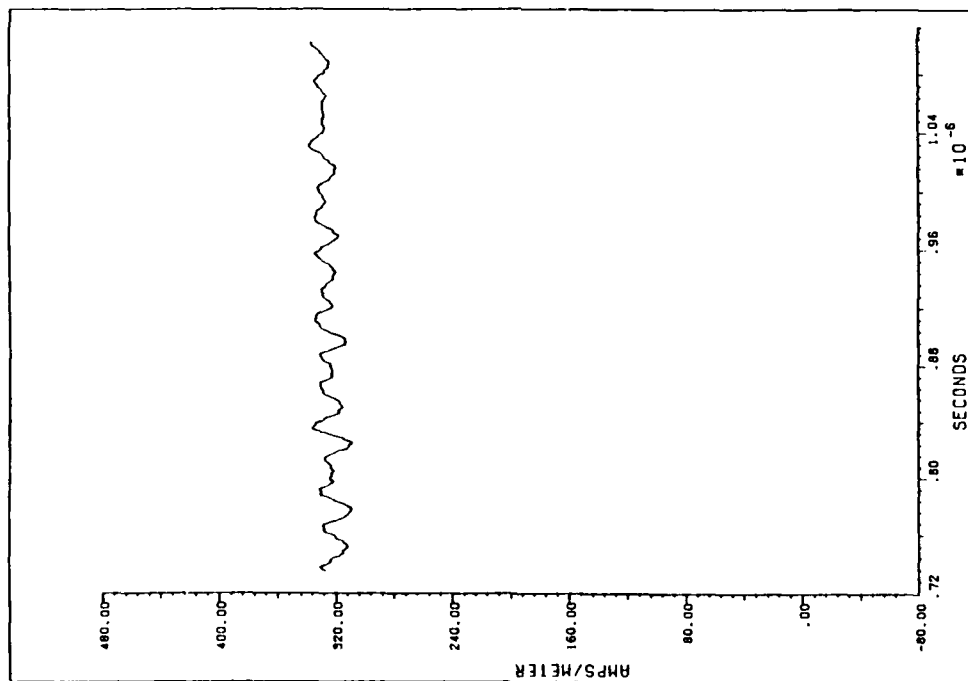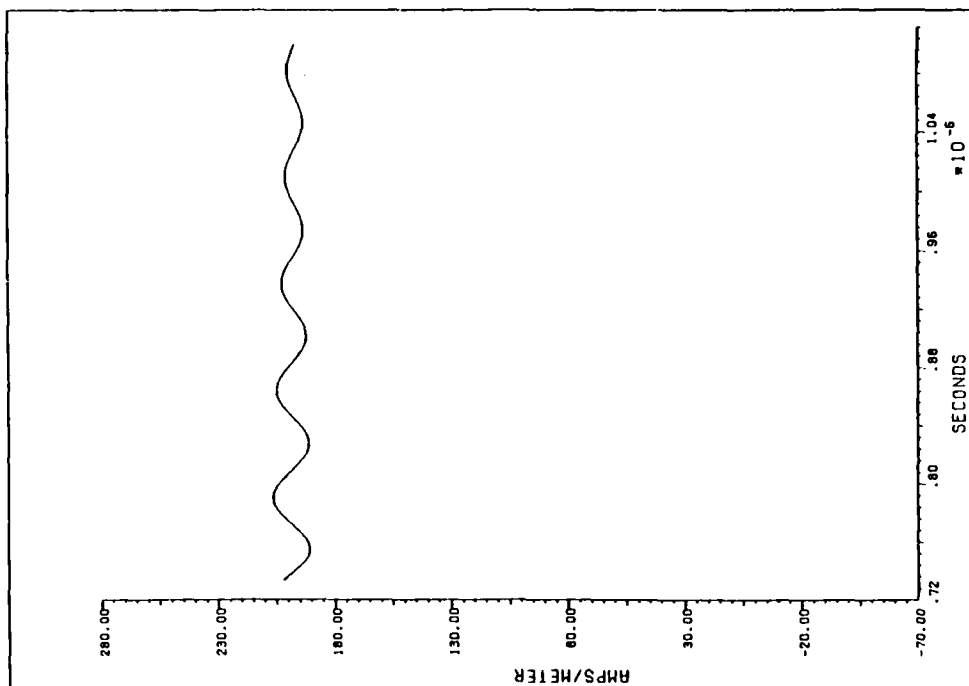
(a) ABC

(b) RBC

Figure 49. Sensor Six, H-field, Vertical Stabilizer, $H_x(22,18,14)$

144
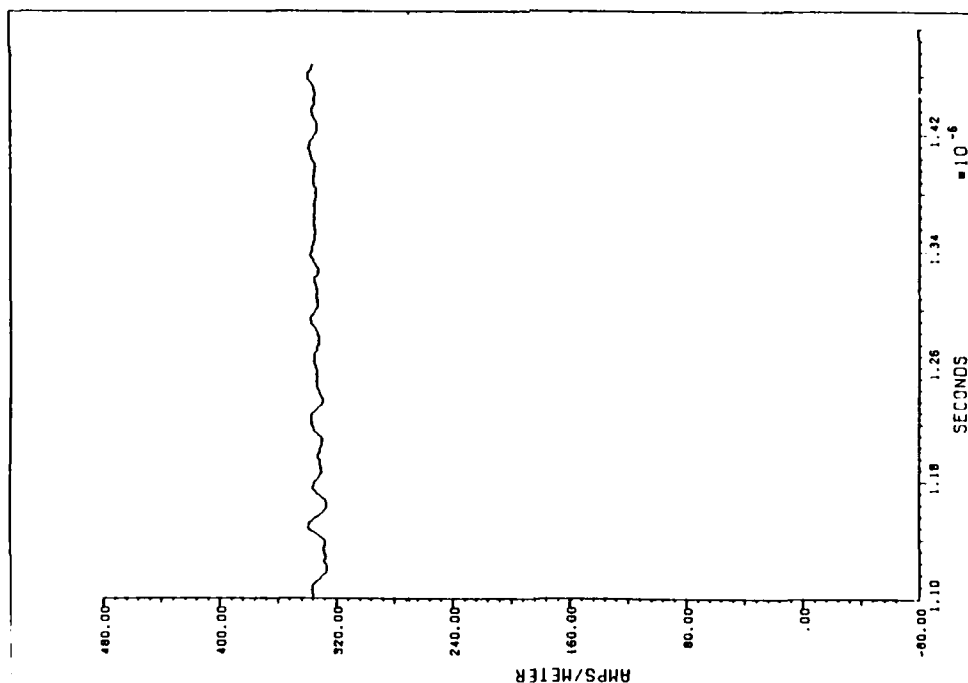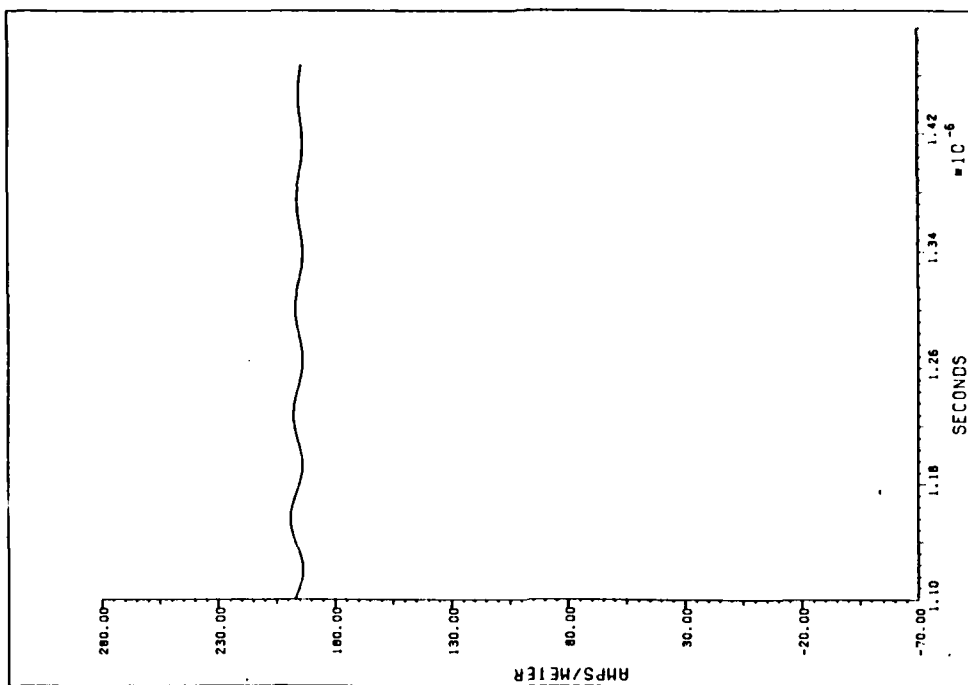
(a) ABC

(b) RBC

Figure 50. Sensor Six, H-field, Vertical Stabilizer, $H_x(22,18,14)$

145
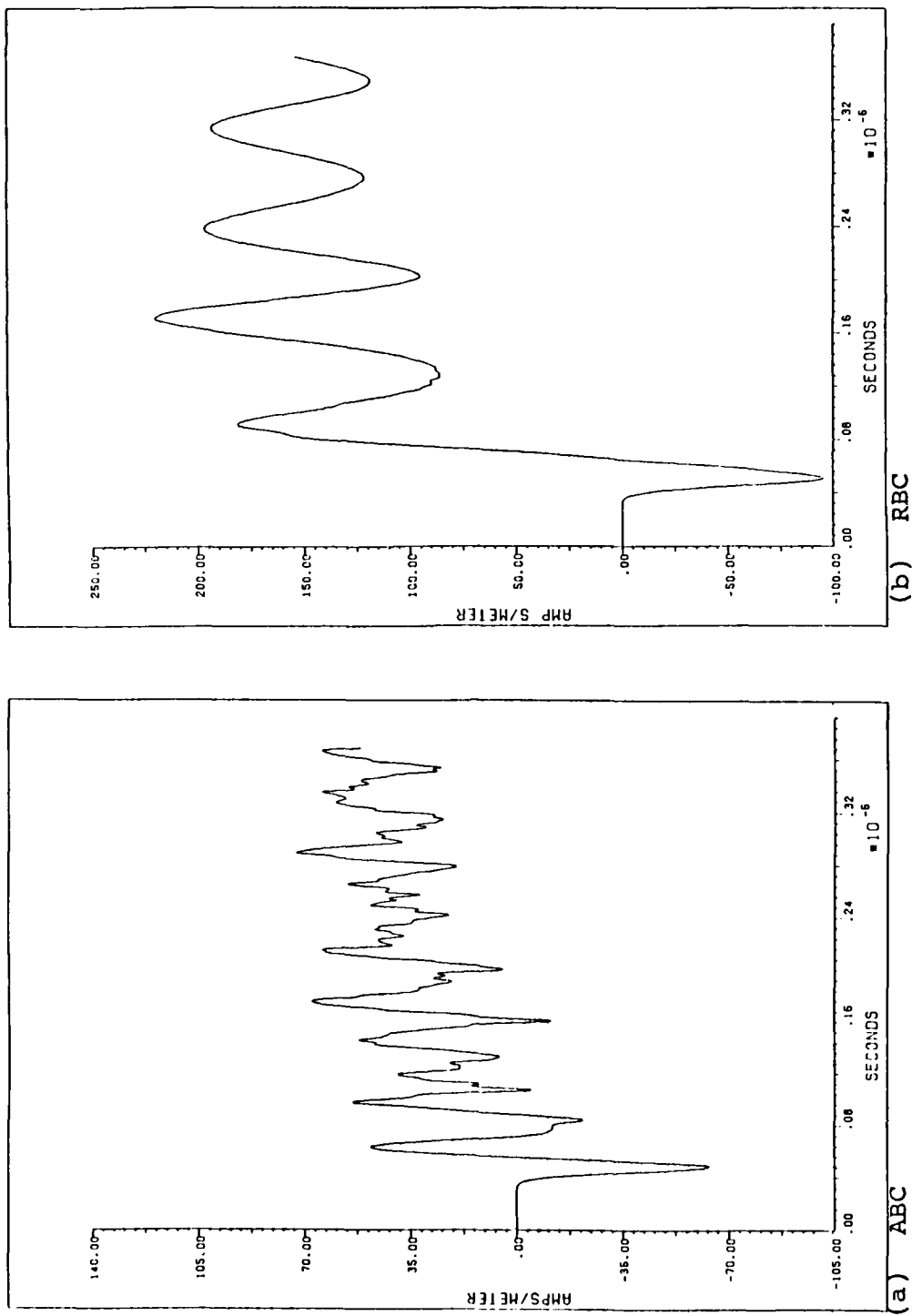
Figure 51. Sensor Seven, H-field, Left Wing, $H_x(18,10,23)$

146
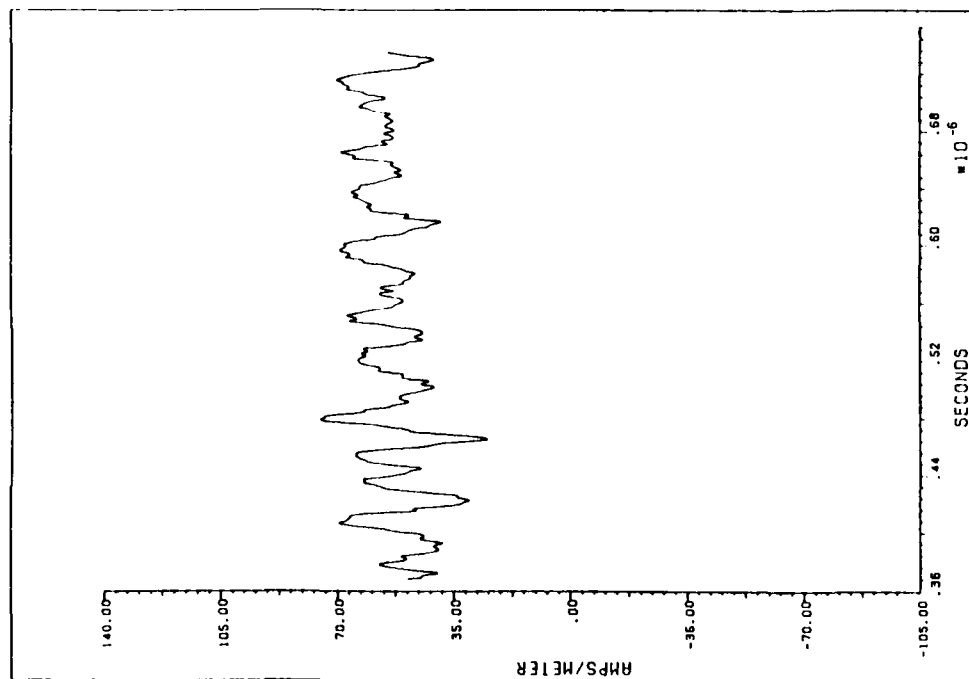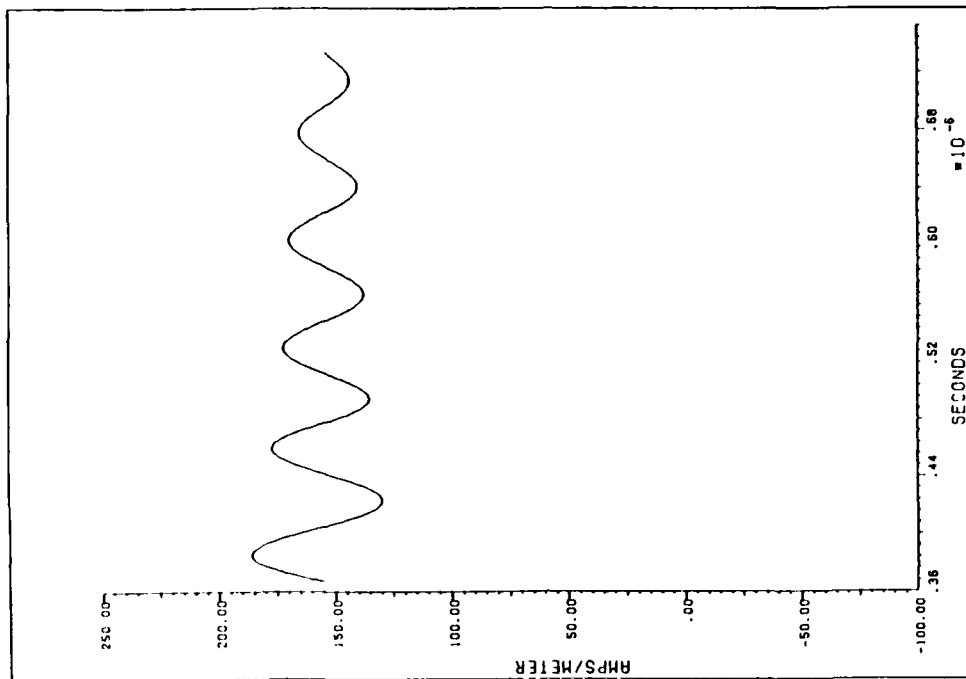
(b) RBC

(a) ABC

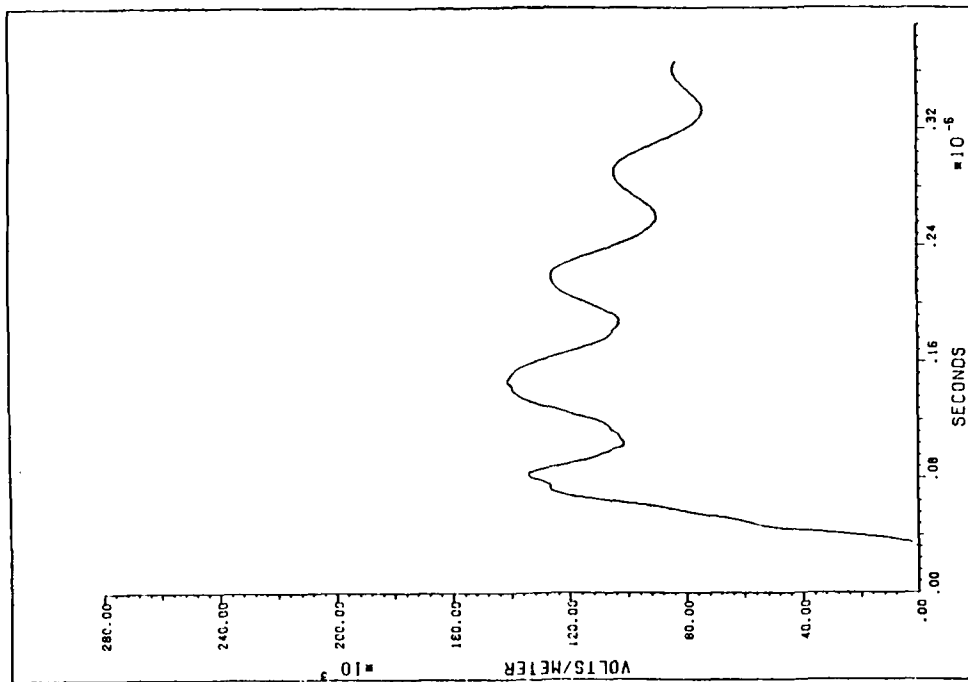Figure 52. Sensor Seven, H-field, Left Wing, $H_x(18,10,23)$

147
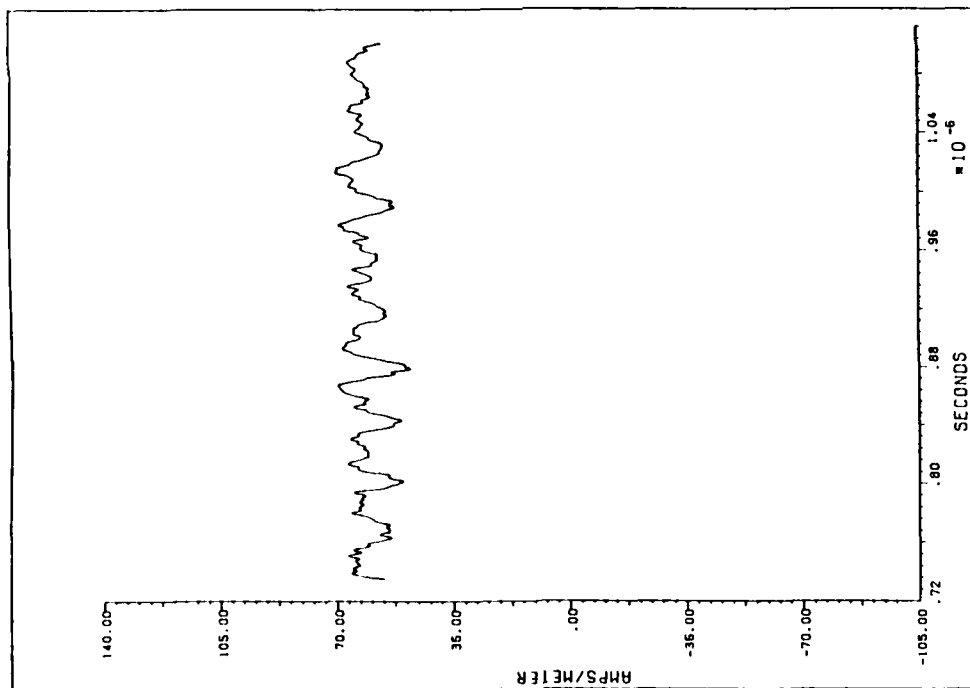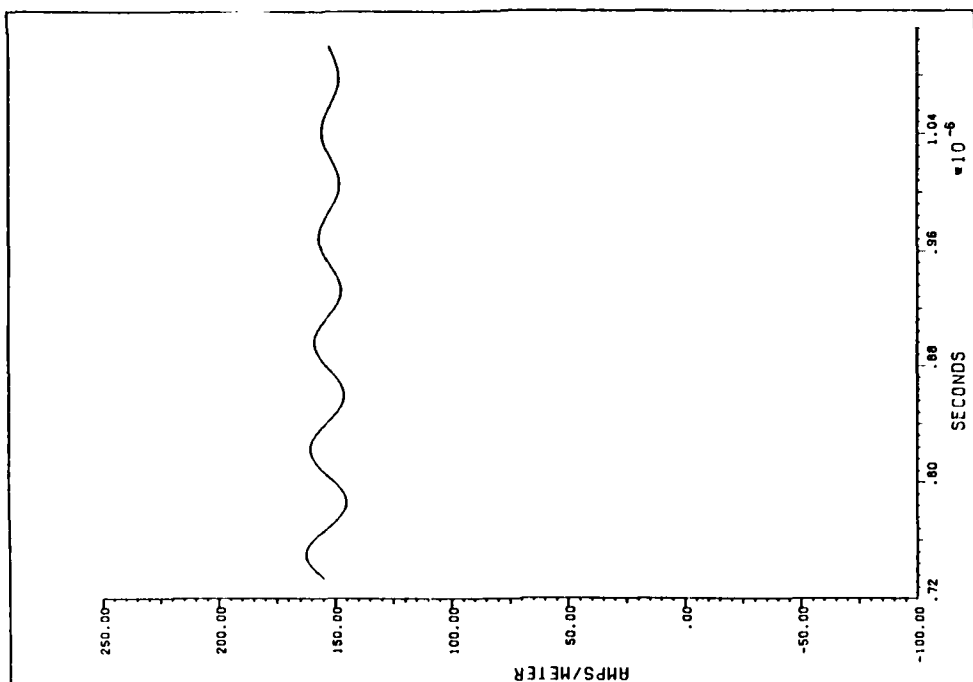
(b) RBC

(a) ABC

Figure 53. Sensor Seven, H-field, Left Wing, $H_x(18,10,23)$

148
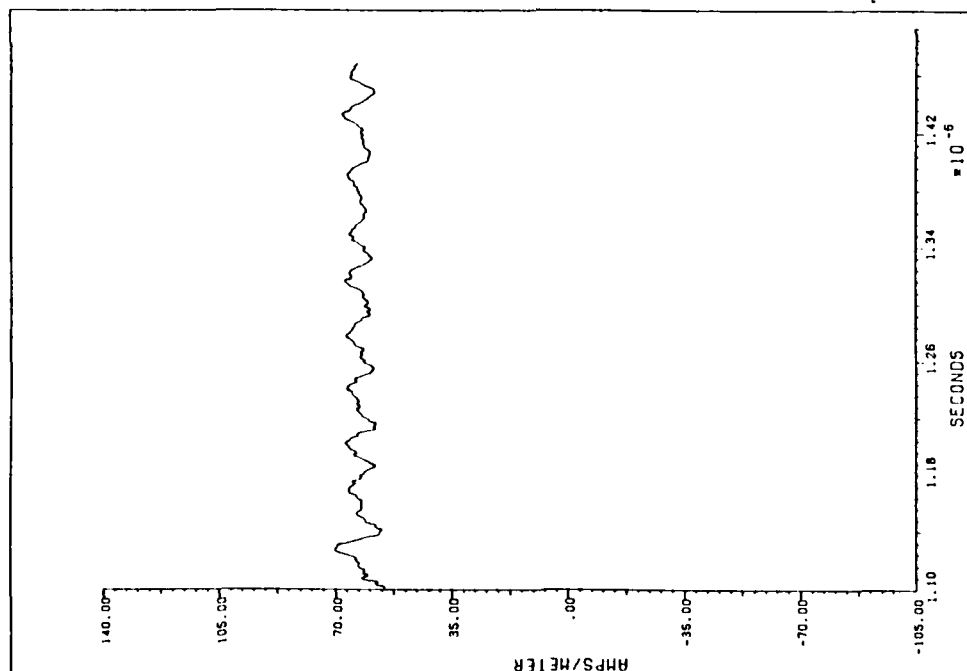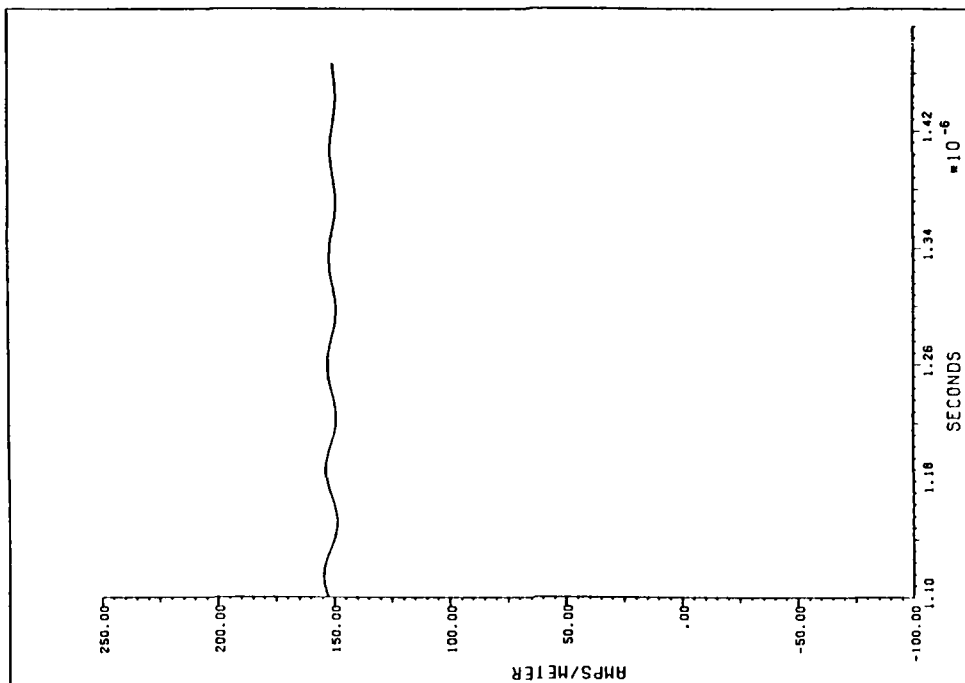
(a) ABC

(b) RBC

Figure 54. Sensor Seven, H-field, Left Wing, $H_x(18,10,23)$

149
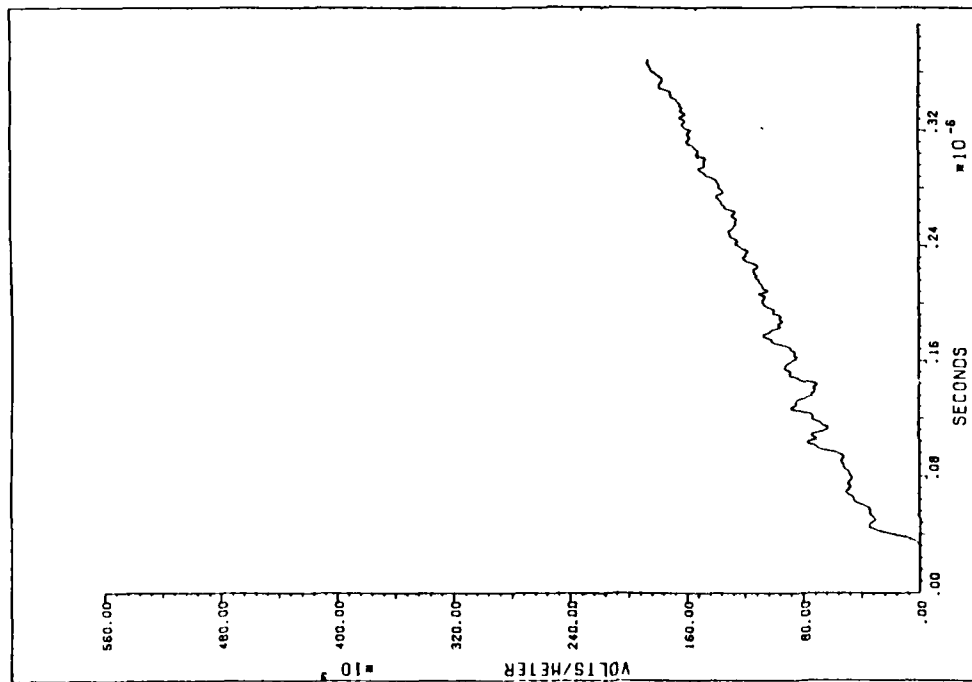
(a) ABC (b) RBC

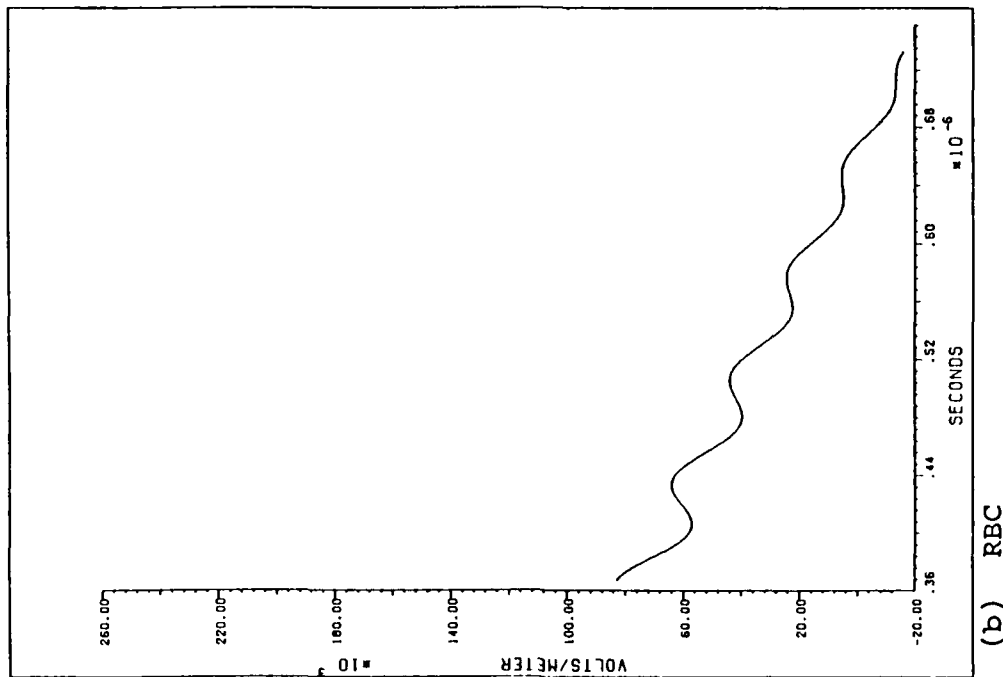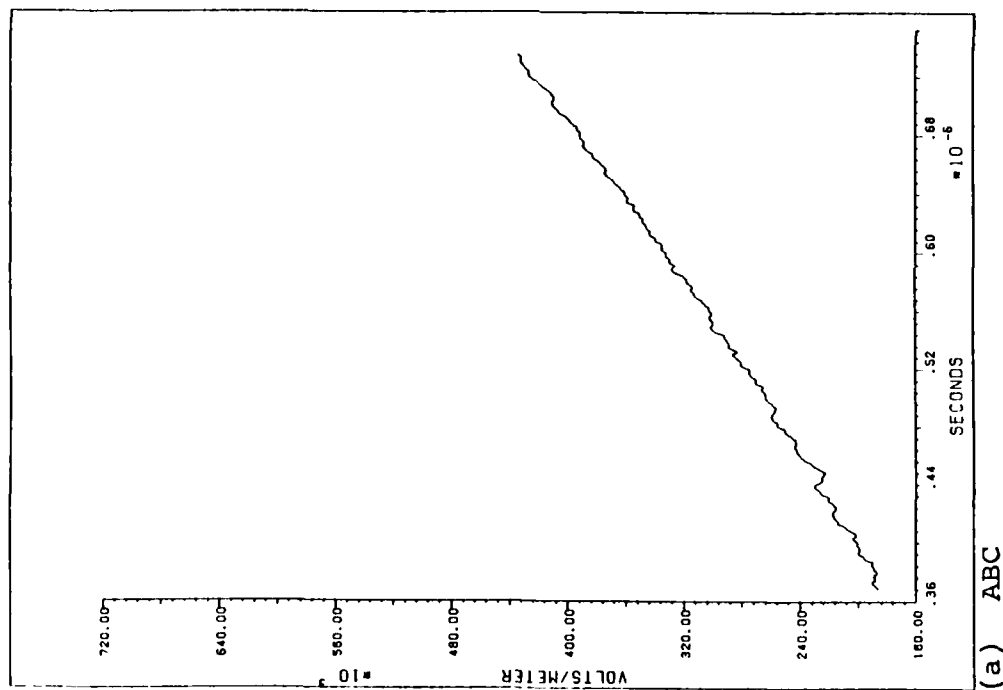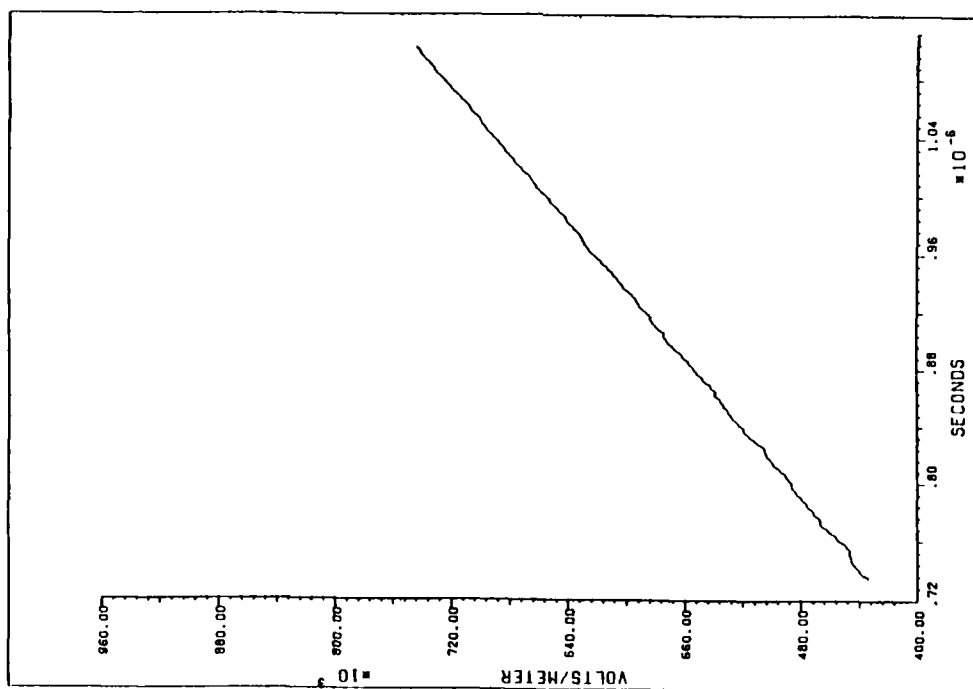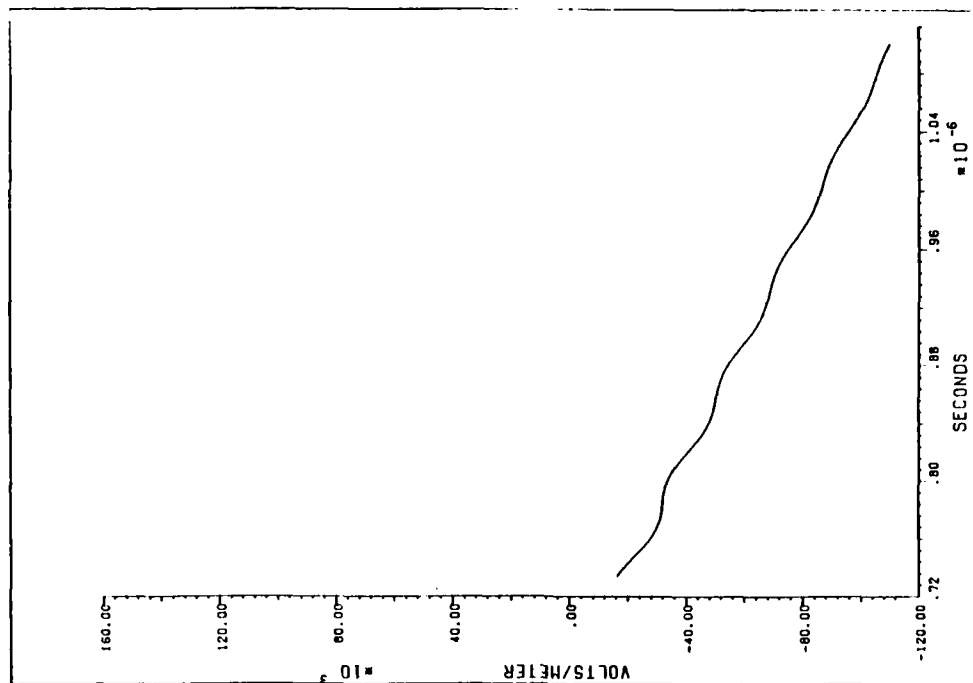Figure 55. Sensor Eight, E-field, Right Wing, $E_y(17,11,10)$

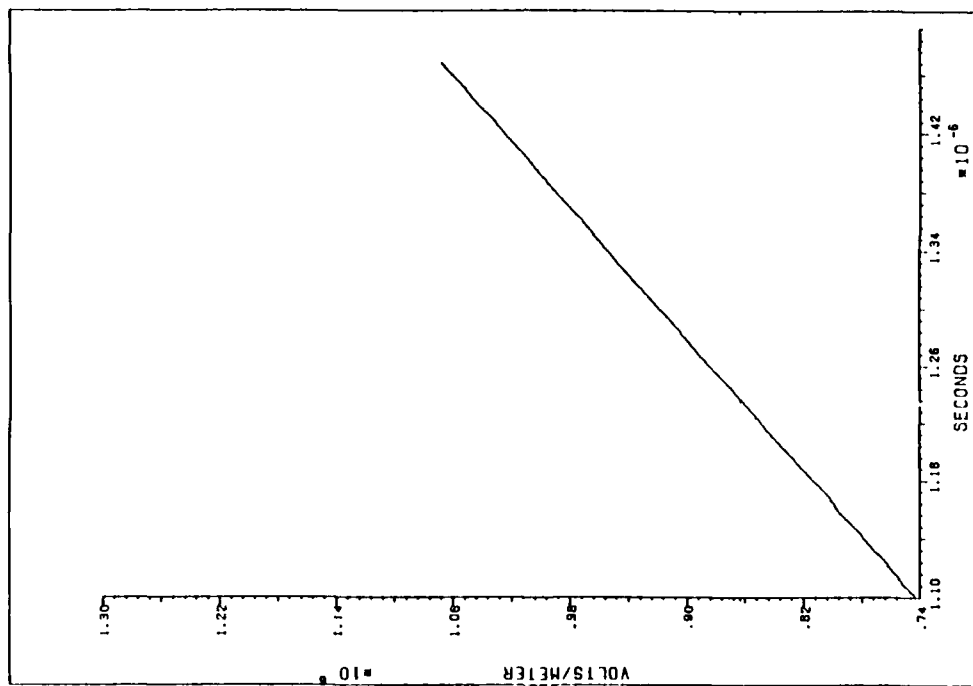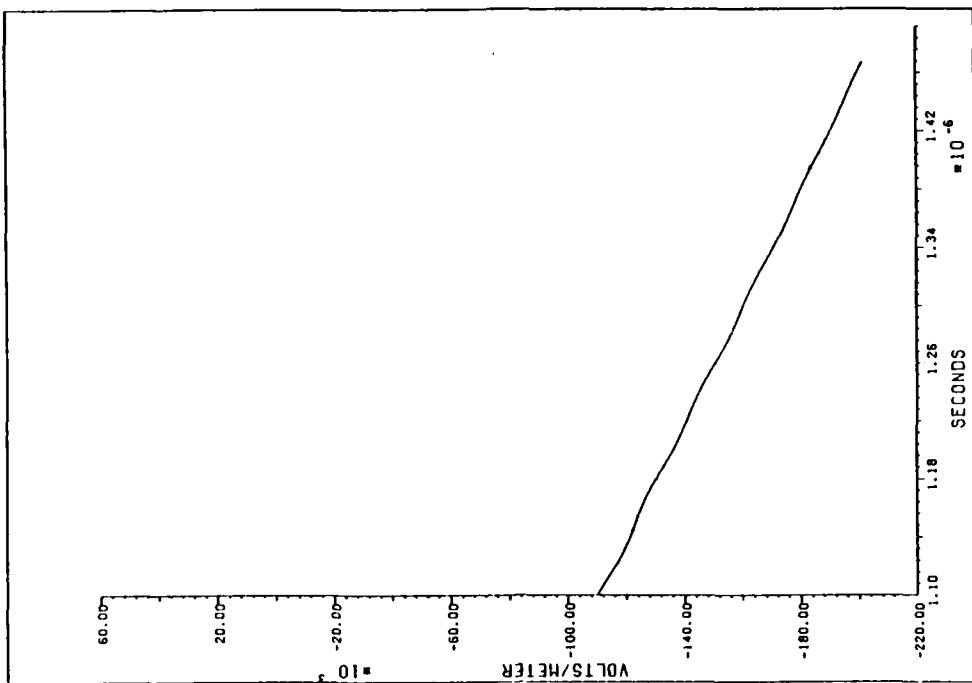Figure 56. Sensor Eight, E-field, Right Wing, $E_y(17,11,10)$

151

(a) ABC

(b) RBC

Figure 57. Sensor Eight, E-field, Right Wing, $E_y(17,11,10)$

152

(b) RBC

(a) ABC

Figure 58. Sensor Eight, E-field, Right Wing, $E_y(17,11,10)$

153

(a) ABC

(b) RBC

Figure 59. Sensor Nine, E-field, Middle Fuselage Top, $E_y(15,13,14)$

(b) RBC

(a) ABC

Figure 60. Sensor Nine, E-field, Middle Fuselage Top, $E_y(15,13,14)$

155

(a) ABC

(b) RBC

Figure 61. Sensor Nine, E-field, Middle Fuselage Top, $E_y(15,13,14)$

156

(a) ABC

(b) RBC

Figure 62. Sensor Nine, E-field, Middle Fuselage Top, $E_y(15,13,14)$

157
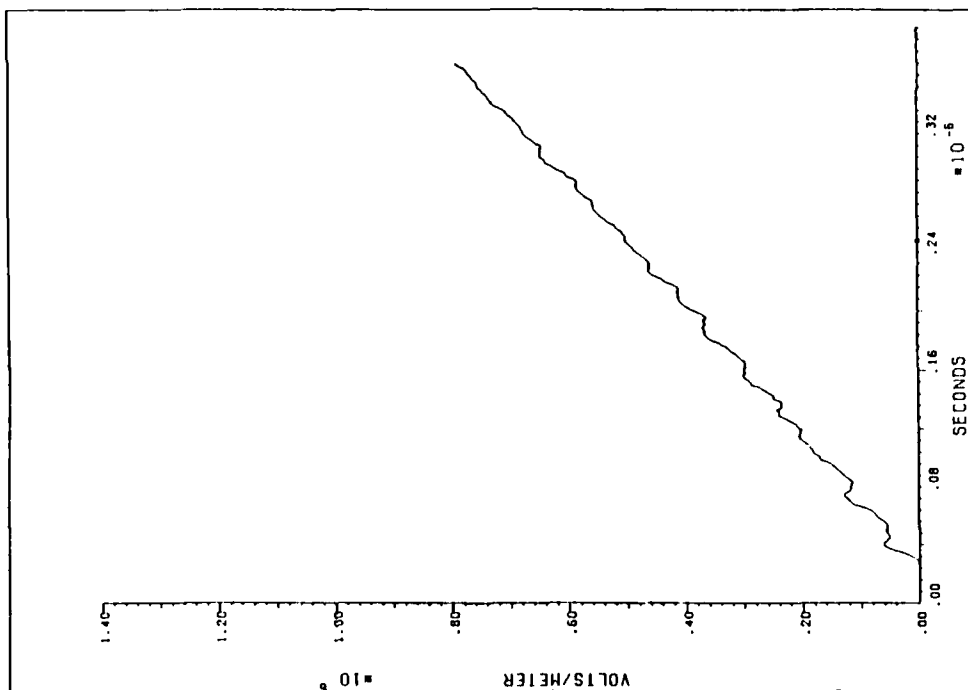
(a) ABC

(b) RBC

Figure 63. Sensor Ten, E-field, Left Wing, $E_y(17,11,18)$

(a) ABC

(b) RBC

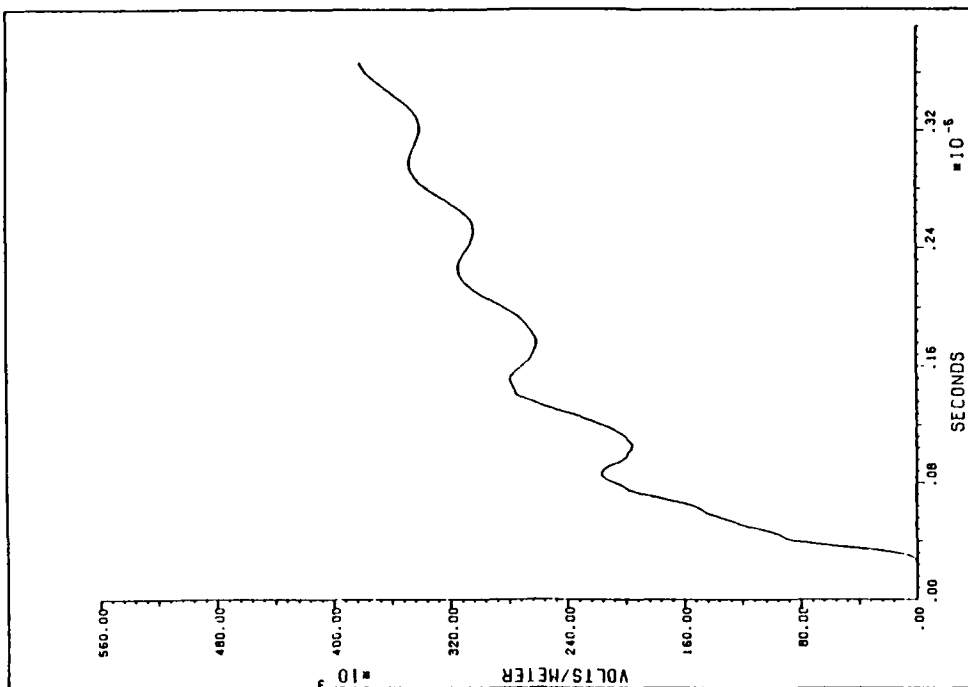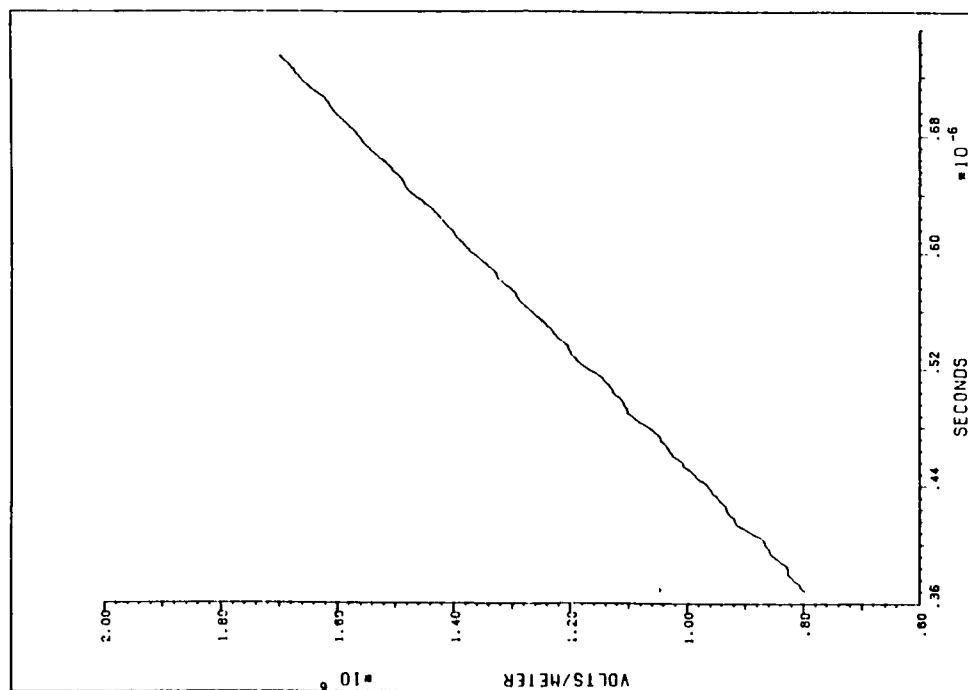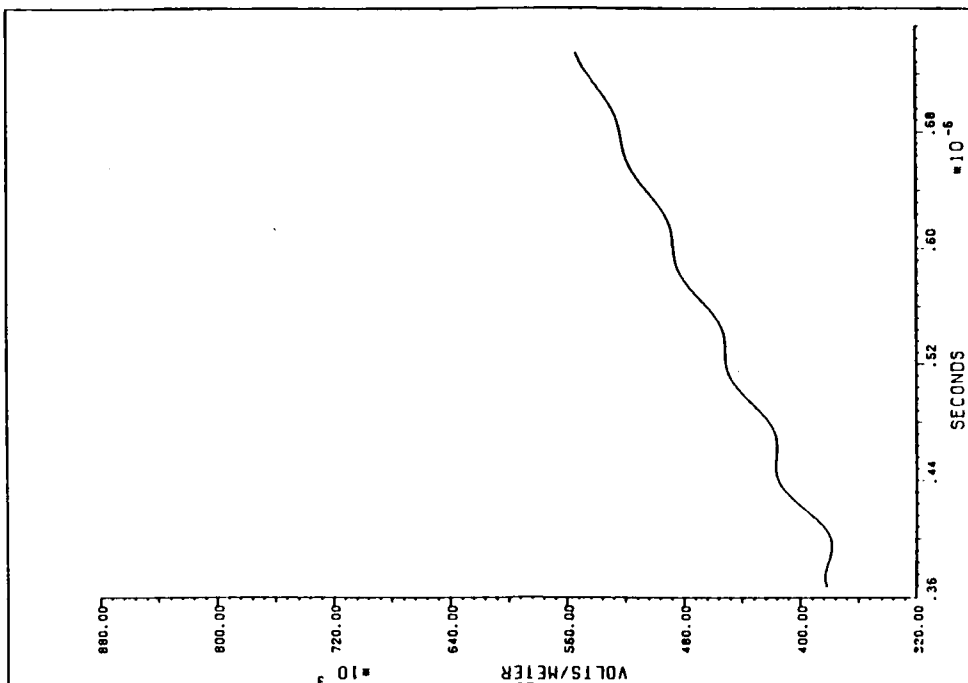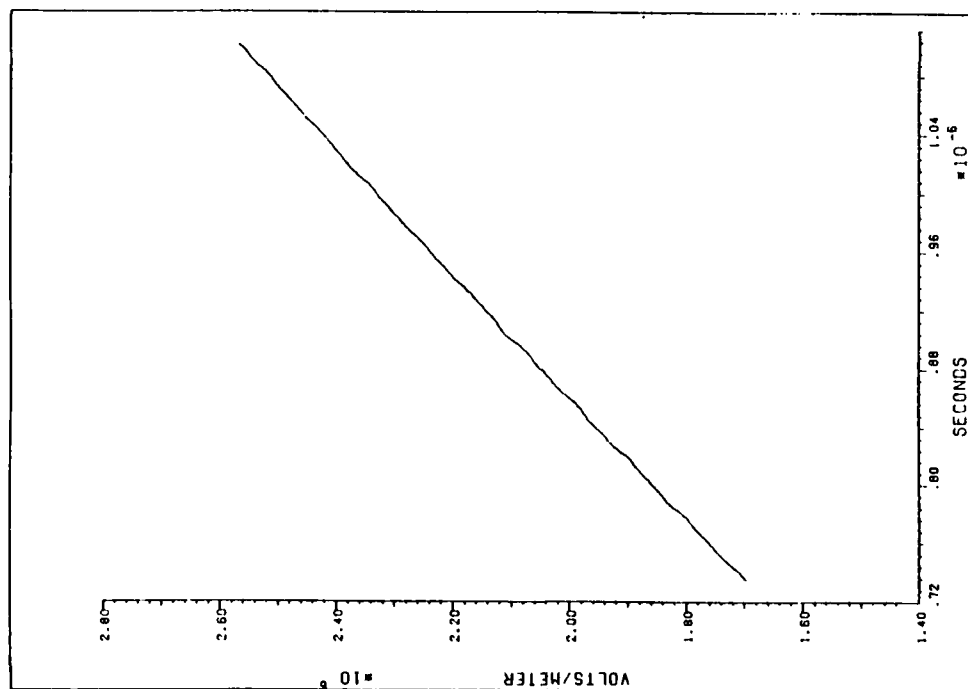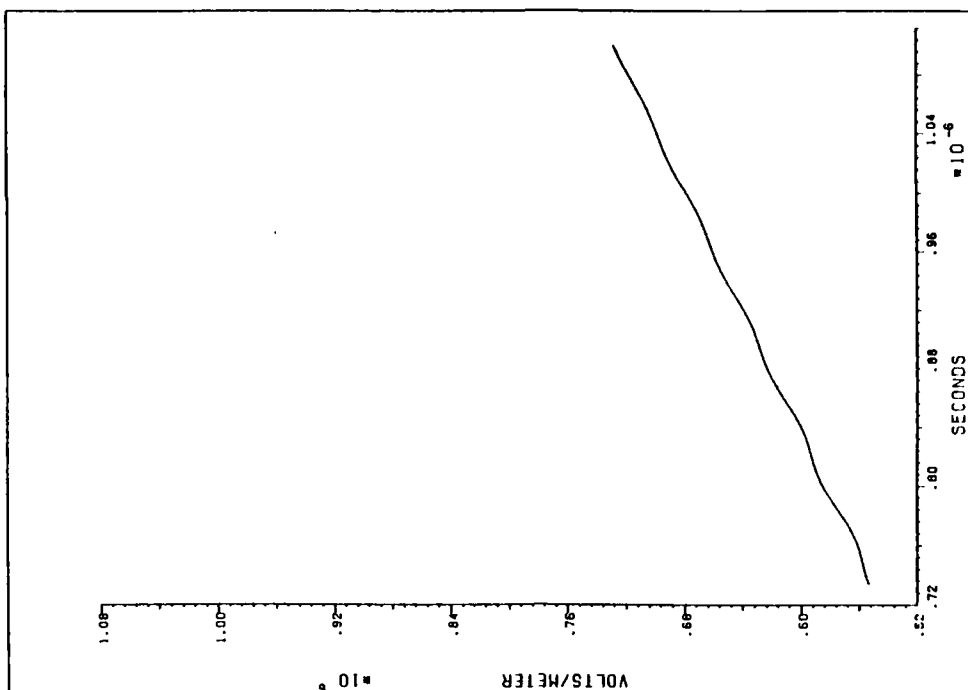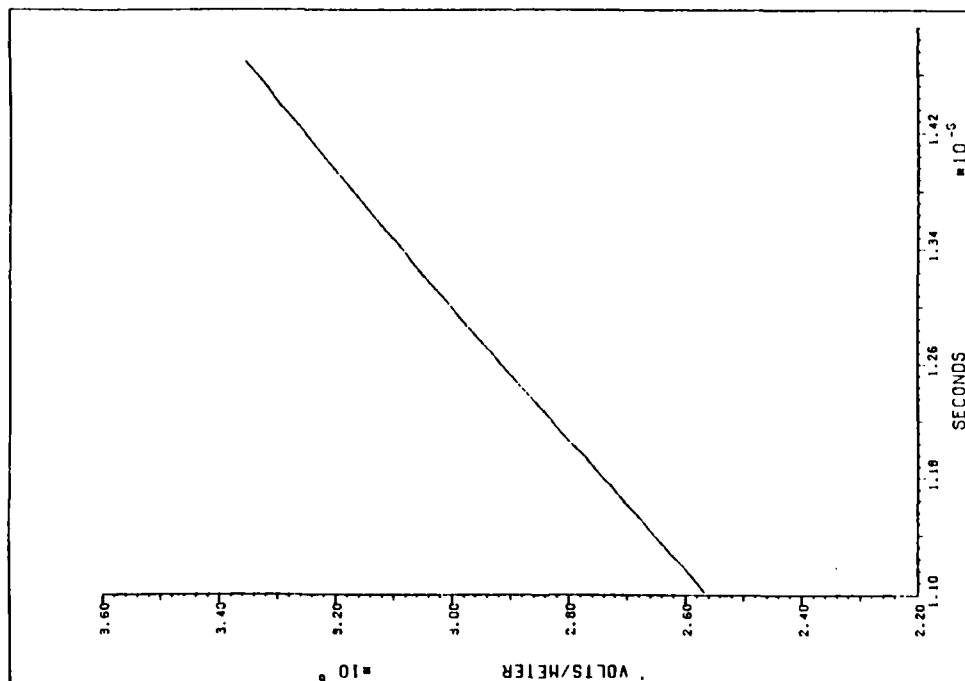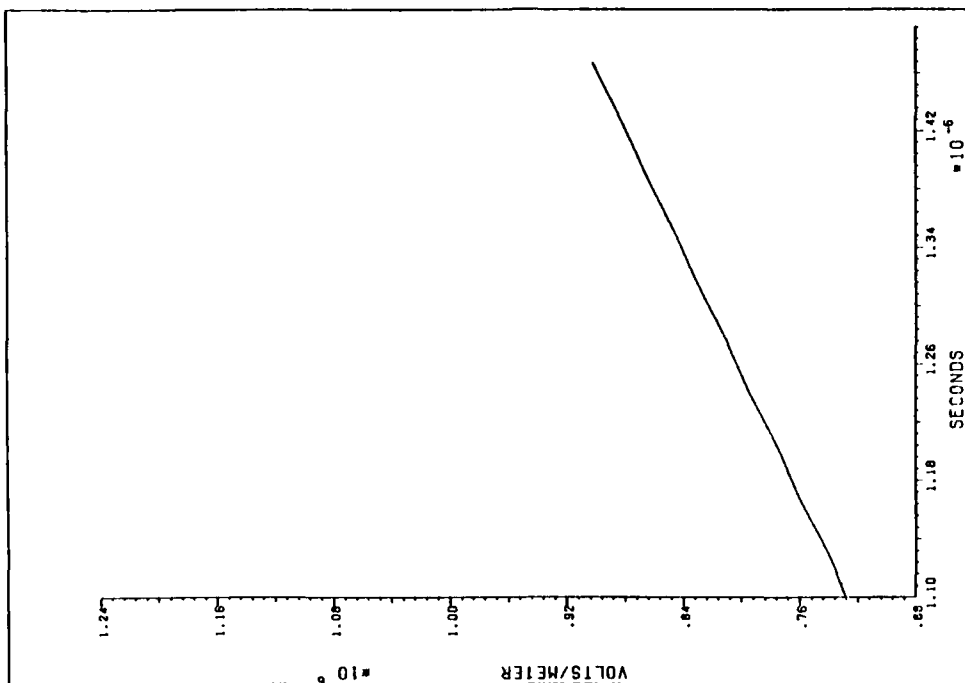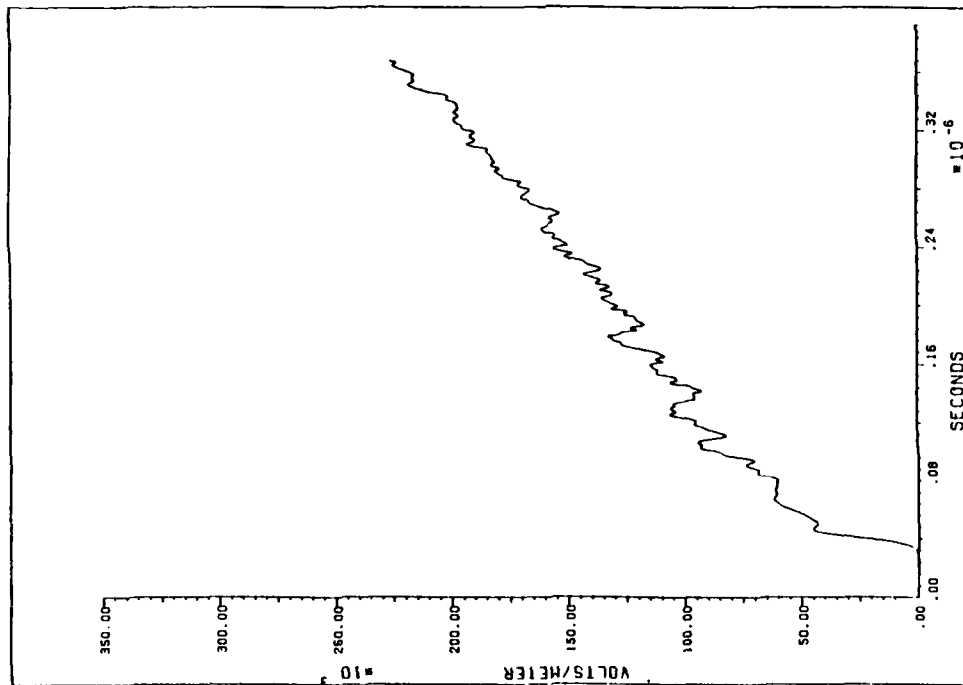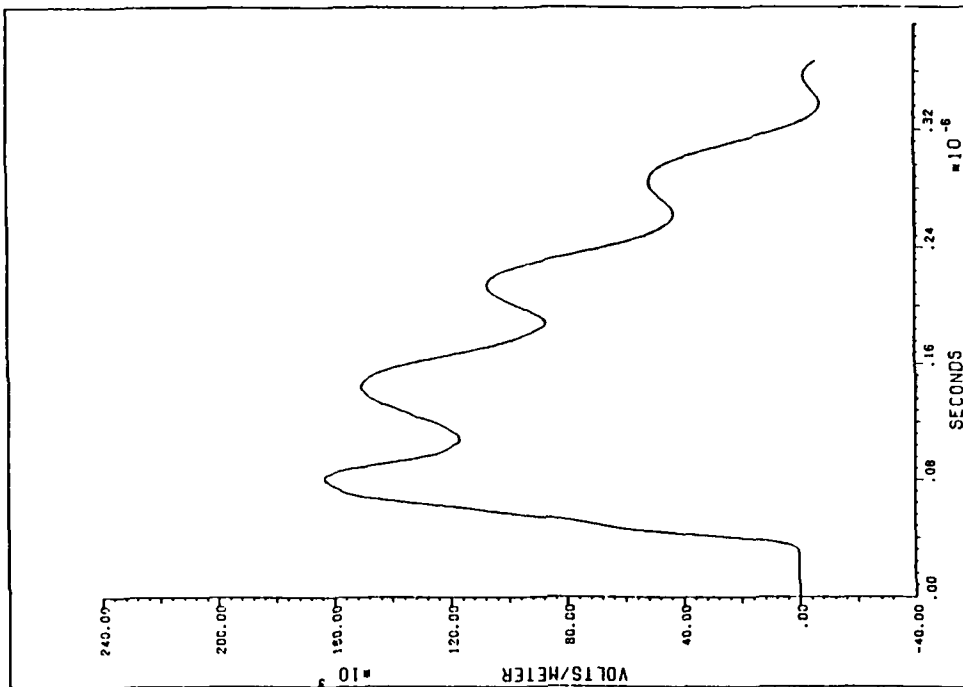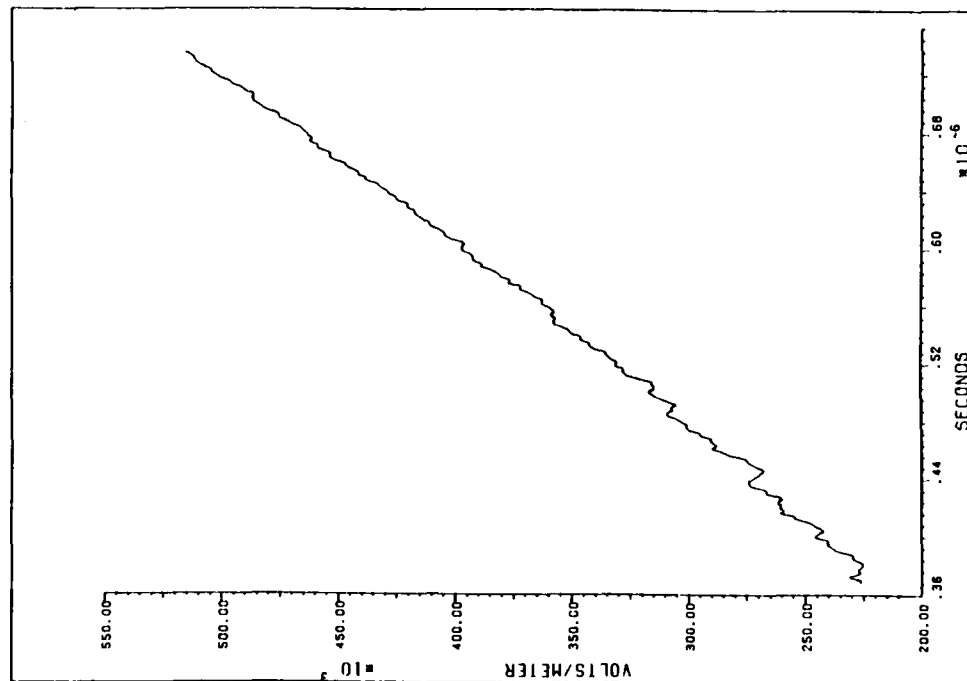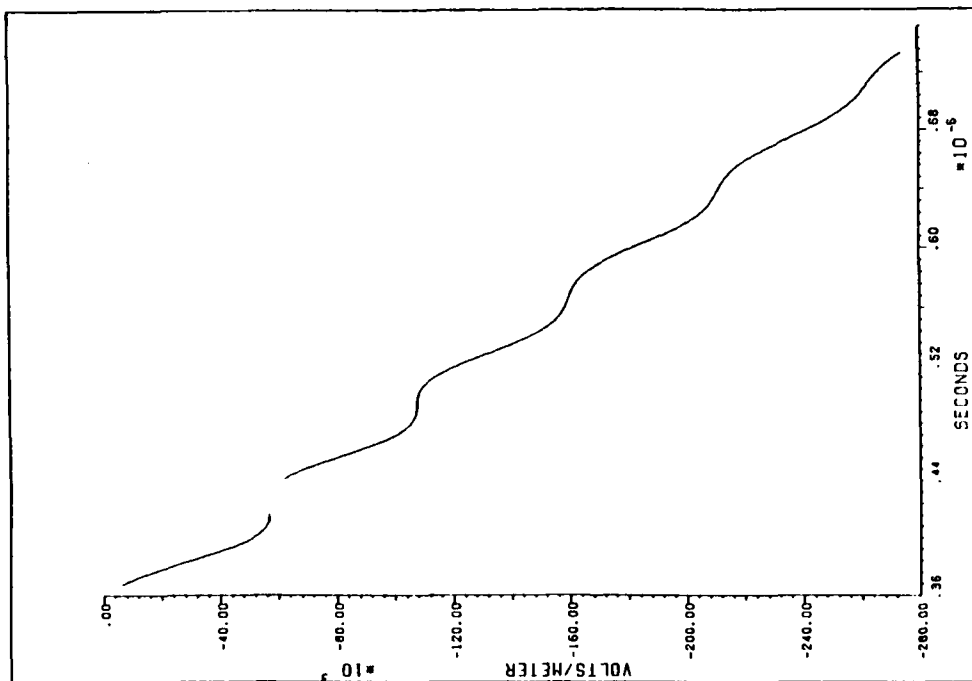Figure 64. Sensor Ten, E-field, Left Wing, $E_y(17,11,18)$
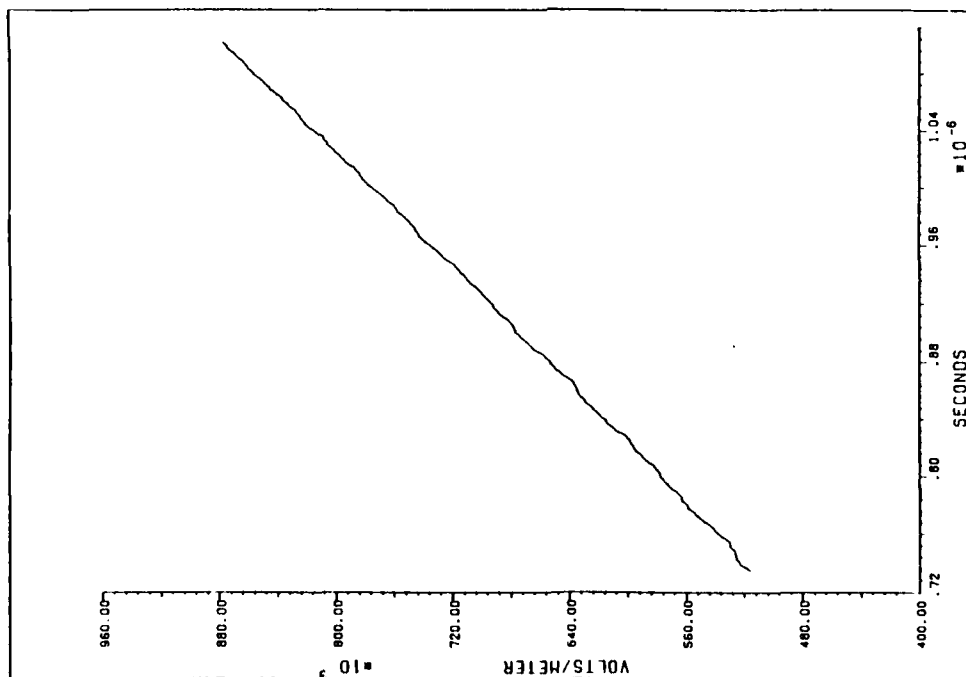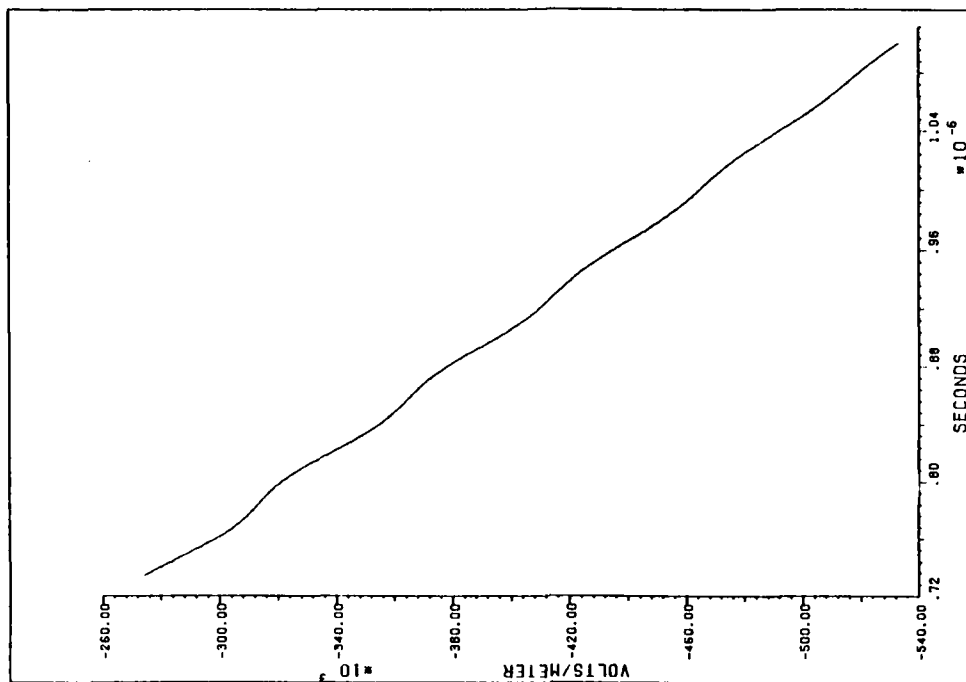
(a) ABC

(b) RBC

Figure 65. Sensor Ten, E-field, Left Wing, $E_y(17,11,18)$

160
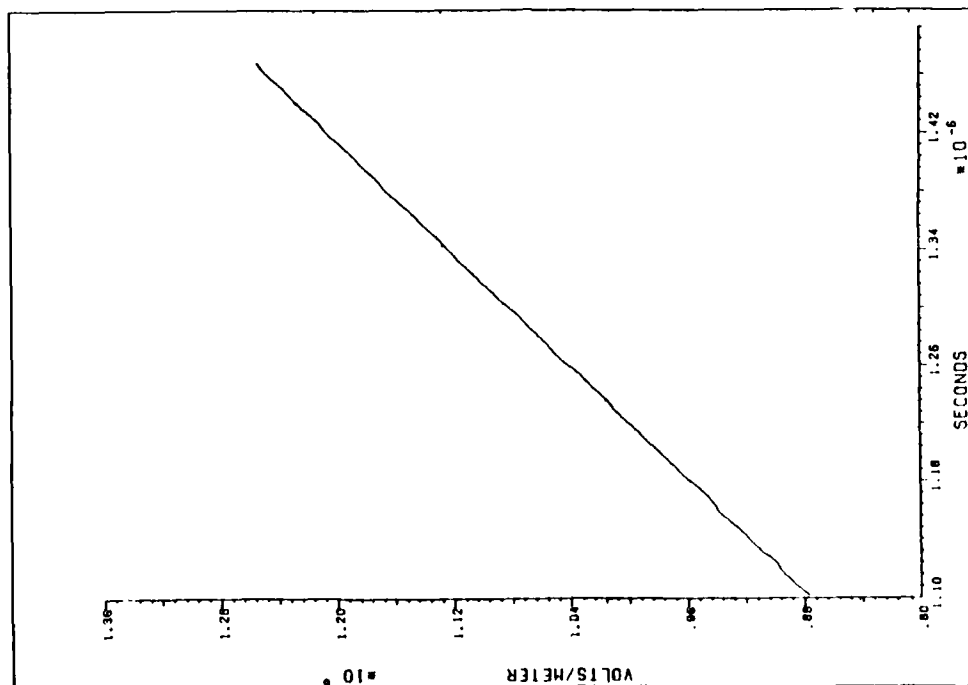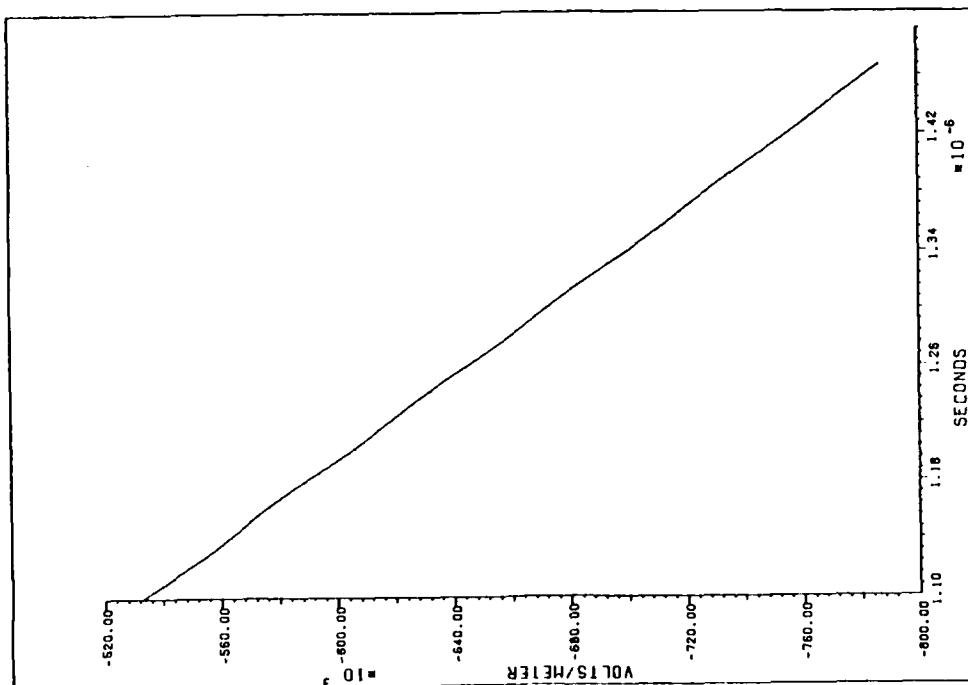
(b) RBC

(a) ABC

Figure 66. Sensor Ten, E-field, Left Wing, $E_y(17,11,18)$

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09	02		Electromagnetic Computer Codes

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20   03

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Wright-Patterson AFB OH 45433

Title: COMPARISON OF ABSORPTION AND RADIATION BOUNDARY CONDITIONS USING

A TIME DOMAIN THREE-DIMENSIONAL FINITE-DIFFERENCE ELECTROMAGNETIC

COMPUTER CODE

Thesis Chairman: Randy J. Jost, 1Lt, USAF
Instructor of Electrical Engineering

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Abstract

The Three-Dimensional Finite Difference (3DFD) computer code
is compared using Absorption Boundary Conditions (ABS)
versus Radiation Boundary Conditions (RBC). This comparison
is made when the 3DFD code is used to study the interaction
of lightning with an aircraft. The 3DFD computer code is a
modified version of Rymes' 3DFD. The aircraft modeled for
the paper is an F-16 'Fighting Falcon'. The ABC used
simulates an infinite free-space by setting the conductivity
of the boundary space to that of distilled water, to
"absorb" the outgoing electromagnetic waves. The RBC
simulates free-space by assigning the boundary fields to a
previously calculated value. The value is calculated with a
parabolic interpolation of three previous field values,
which are offset in space. Therefore, the calculated value
is also extrapolated to account for the time delay and
position change. The results of incorporating RBC were
dramatic. The ten locations sampled for the test showed
marked improvement in the waveforms when using RBC's.
Depending on the purpose of the analysis, this improved
waveform output may be overshadowed by the 25% increase in
CPU time that is needed for the more sophisticated RBC.

END

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